AD-A277 608

PAGE Approved for public release; distribution unlimited.

Form Approved OMB No. 0704-0188

Public report... gathering and... collection of in... Davis Highway ... per response, including the time for reviewing instructions, searching existing data sources, ...on of information. Send comments regarding this burden estimate or any other aspect of this ...n Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson ...t and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 1994	final technical report 3/15/90-3/14/93

4. TITLE AND SUBTITLE
The Cognitive, Perceptual, and Neural Bases of Skilled Performance

5. FUNDING NUMBERS
AFOSR 90-0175
3484
HS
61102D

6. AUTHOR(S)
Stephen Grossberg, Principal Investigator

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Boston University
Center for Adaptive Systems
111 Cummington Street, Room 244
Boston, MA 02215

8. PERFORMING ORGANIZATION REPORT NUMBER
AEOSR-TR- 94 0067

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
Life Sciences Directorate
Bolling AFB, DC 20332

Dr. John F. Tangney

88Pd
413
123

94-09337

11. SUPPLEMENTARY NOTES

DTIC ELECTE MAR 28 1994 S B D

12a. DISTRIBUTION / AVAILABILITY STATEMENT
...proved for public release; ...tribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This three-year project partially supported three week-long international scientific meetings and courses on neural network research, 4 research books, more than 100 research articles, 68 Boston-area colloquia, 10 completed PhD theses, and the training of more than 20 graduate students. The research spanned a coordinated program of experimental and modeling studies of how the brain autonomously carries out intelligent behaviors in real-time in response to changing environmental contingencies. Neural models of 3-D vision and figure-ground separation, motion perception, visual search, speech perception, working memories for storage of temporal sequences, supervised and unsupervised learning of recognition categories and predictions in response to nonstationary data, arm movement control, and quadruped gait transitions were developed. Technology transfers were made to processing of artificial sensor data, automatic target recognition, several industrial applications, and the control of mobile robots.

94 3 25 059

DTIC QUALITY INSPECTED 1

14. SUBJECT TERMS	15. NUMBER OF PAGES
	88 pages
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified		

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std 239-18
298-102

FINAL SCIENTIFIC REPORT

Contract AFOSR 90-0175

THE COGNITIVE, PERCEPTUAL, AND NEURAL BASES OF SKILLED PERFORMANCE

March 15, 1990—March 14, 1993

Principal Investigator: Stephen Grossberg
Wang Professor of Cognitive and Neural Systems
Professor of Mathematics, Psychology,
and Biomedical Engineering
Director, Center for Adaptive Systems
Chairman, Department of Cognitive and Neural Systems
Boston University
111 Cummington Street
Boston, MA 02215
(617) 353-7857

TABLE OF CONTENTS

I. REPORT SUMMARY

This report reviews progress from the Boston University and Northeastern University research groups of our AFOSR University Research Initiative grant. The subcontract to Professor John Daugman of Harvard and Cambridge Universities will be separately filed. The report lists books and articles, summaries of research, PhD students who were partially supported by the grant, conferences and colloquia that were partially supported by the grant, and selected abstracts of key articles.

1. Three Neural Networks Courses and Conferences at the Wang Institute

In May of 1990, 1991, and 1992, week-long international courses and conferences on neural networks were held at the Wang Institute of Boston University. The purpose of the courses was to introduce scientists, engineers, and students to the core principles, mechanisms, and architectures of neural network research. The course was attended each year by a capacity crowd of 300 people from many countries and states of the USA.

The three conference topics were Neural Networks for Automatic Target Recognition; Neural Networks for Vision and Image Processing; and Neural Networks for Learning, Recognition, and Control. The 1992 course was typical in offering 10 lecturers who lectured 8 hours a day, interspersed with active discussions during meals and after each day's dinner. The conference presented 19 invited lecturers whose topics ranged from the biological to the technological, and 69 refereed poster presentations. Copies of the three course and conference programs are attached.

The 1991 conference, on vision and image processing, led to a book of the same name that was published to good reviews by MIT Press. (See book 2 in the publications list.) The book's preface follows:

EDITORIAL PREFACE
Neural Networks for Vision and Image Processing
Cambridge, MA: MIT Press, 1992

This book provides a resource for teaching and research about the vitally important areas of biological vision and image processing technology. Vision is one of the most important sources of information for supporting intelligent human behavior, as well as a key competence for designing new types of intelligent computers and machines. The book brings together recent research contributions from leading experimentalists and modelers, who presented their results at a conference in May, 1991 at the Wang Institute of Boston University. The interdisciplinary nature of the conference is reflected in its range of topics, from visual neurobiology and psychophysics through neural and computational modelling to technological applications. Such a program format acknowledges the important role that biological data and models have had on the development of technological applications, and the role that computational models have had on guiding the progress of experimental vision research.

The book's chapters mirror this interdisciplinary perspective. They are grouped according to the phenomena and problems that they address, rather than the methods that are used to analyse them. The first eleven chapters concern visual processes that are often described as "preattentive". Such processes tend to occur at earlier stages of brain processing, albeit stages that can include visual cortex, and can proceed automatically without the intervention of attention, learning, and object recognition The remaining six chapters consider "attentive" processes, that tend to occur at later stages of brain processing, and that critically involve mechanisms of attention, learning, and object recognition. The distinction between preattentive and attentive processes is one of emphasis, at least in psychophysical studies of human vision, because every human response to a sensory input engages all the neural stages that occur between input and output. The distinction is nonetheless a useful one, and it has become increasingly well articulated with every advance in correlating visual percepts with the neural processing stages that generate them.

The "preattentive" chapters are themselves broken into two groupings. The first six chapters primarily consider processes underlying the perception of static images. Brightness, color, texture, shading, stereo, and form are subjects of inquiry here. The next five chapters consider processes underlying the perception of moving images. Some of these chapters also analyse why static and moving images need to be processed by different, but parallel, mechanisms.

All of the chapters address the fact that visual properties are not processed independently. For example, Stuart Anstis describes some of the remarkable effects on perceptual recognition of reversing image brightness and color. Jacob Beck and William Goodwin document how texture segregation depends on the interchange of light and dark values, or red and green hues in an image. Farley Norman and James Todd discuss psychophysical experiments that shed light on a number of the perceptual constraints and processes that are relevant in human perception of three-dimensional form, both of static and moving images. V.S. Ramachandran explores the perception of form through experiments that include contrast reversals, illusory contours, filling-in, and apparent motion.

Alex Pentland provides an analysis of models for analysing vision as a dynamic system, rather than a static one, and discusses a model for surface representation that includes concepts from Kalman filtering and orthogonal wavelets, as well as their possible neural interpretation in terms of receptive fields and cortical networks. Another new approach to understanding surface representation, especially in the context of the shape-from-shading problem, is presented by Pierre Breton, Lee Iverson, Michael Langer, and Steven Zucker, who combine properties of shading flow fields, a concept related to networks of oriented receptive fields, with relaxation labelling, a form of cooperative computation, to cope concurrently with surface, material, and light source compatibility constraints. The final chapter in the static vision cluster is by Stephen Grossberg and Lonce Wyse, who describe a biologically motivated model for parallel separation of multiple scenic figures from one another and from their background onto different surface representations, while suppressing scenic noise, by using a combination of opponent processing, boundary segmentation, and filling-in mechanisms.

The first chapter concerning the perception of moving objects is by Paolo Gaudiano, who also uses mechanisms of opponent processing to provide a unified explanation of retinal data about X and Y cells, particularly differences in their sustained and transient responses. The fact that both static figure-ground separation and the retinal processing of transient information both use similar opponent processing mechanisms illustrates the need for interdisciplinary vision research that clarifies how similar neural mechanisms can be used for different perceptual purposes. David Fay and Allen Waxman consider the neurodynamics of image velocity extraction using a multi-level model that also begins with retina-like processing, and implement a model for video rate image velocity extraction on a PIPE computer.

The next chapter, by Stephen Grossberg, analyses why parallel cortical systems are needed to process information about static and moving objects, and outlines a unified model for these parallel streams in terms of a global symmetry principle that has enabled explanations to be offered of many previously intractable perceptual and neural data, including data about illusory contours, filling-in, apparent motion, and perceptual aftereffects. The chapter by Stephen Grossberg and Ennio Mingolla further develops a model of the cortical motion processing stream to suggest a solution of the global aperture problem, which clarifies how cooperative processes can contextually eliminate local ambiguities in the computation of motion direction.

The chapter by Robert Desimone begins the cluster concerned with attentive vision and pattern recognition by summarizing recent neurobiological experiments and concepts concerning attentive processing by the inferior temporal (IT) cortex, area V4 of the prestriate visual cortex, and the pulvinar. Gail Carpenter, Stephen Grossberg, Natalya Markuzon, John Reynolds, and David Rosen then describe how adaptive resonance theory (ART) networks can learn to categorize and focus attention upon predictive combinations of visual features, and can use predictive feedback to drive a memory search leading to new attentional foci that conjointly minimize predictive error and maximize predictive generalization. The chapter by Stephen Grossberg and David Somers describes how cortical models of preattentive boundary segmentation and attentive object recognition can rapidly bind spatially distributed feature detectors into synchronized oscillations within a single processing cycle, and thereby prevent these features from becoming attached to representations of the wrong visual objects. Alan Rojer and Eric Schwartz describe a computational model of visual attention capable of rapidly selecting motor fixation points for a space-variant sensor which uses Bayesian and Hough transform concepts in a hardware system for reading license plates of moving vehicles in real time. David Casasent describes neural networks for learning and recognition that are amenable to implementation in optical hardware. Robert Hecht-Nielsen describes a neural network for image analysis that has been applied to problems of sorting, target recognition, and medical image analysis.

We wish to thank the authors for their careful selection and preparation of the material in their chapters, Cynthia Bradford and Diana Meyers at the Center for Adaptive Systems for their help in preparing the text and index, and the Life Sciences Directorate of AFOSR for its financial support of the conference.

Gail A. Carpenter
Stephen Grossberg
Boston, Massachusetts
January, 1992

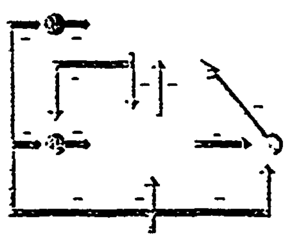
BOSTON UNIVERSITY

A World Leader in Neural Network Research and Technology
Presents

Two Major Events on the Cutting Edge

Neural Networks: From Foundations to Applications

May 6 - 11, 1990
A self-contained systematic course by leading neural architects
who know the field as only its creators can.



Neural Networks for Automatic Target Recognition

May 11 - 13, 1990
An international research conference presenting INVITED and CONTRIBUTED papers,
herewith solicited, on one of the most active research topics in technology today.

Each event offers a unique opportunity to master vital information.
Both events together provide a week of rare intellectual
excitement and practical hands-on experience.

A limited number of student fellowships are available.

Sponsored by Boston University's Wang Institute, Center for Adaptive
Systems, and Graduate Program in Cognitive and Neural Systems
with partial support from the Air Force Office of Scientific Research.

Neural Networks: From Foundations to Applications

May 6 - 11, 1990

This self-contained systematic five-day course is based on the world's leading graduate curriculum in the technology, computation, mathematics, and biology of neural networks. Developed at the renowned Center for Adaptive Systems (CAS) and the graduate program in Cognitive and Neural Systems (CNS) of Boston University, the course will be taught by the full CAS/CNS faculty, as well as by distinguished guest lecturers. An extraordinary range and depth of models, methods, and applications will be presented. Evening discussion sessions with CNS faculty, and presentations by industry leaders in neural network technology will be offered.

COURSE FACULTY FROM BOSTON UNIVERSITY

STEPHEN GROSSBERG, Wang Professor of CNS, as well as professor of mathematics, psychology, and biomedical engineering, is one of the world's leading neural network pioneers and most versatile neural architects. The founder and 1988 president of the International Neural Network Society (INNS), he is also founder and coeditor in chief of the INNS journal Neural Networks, an editor of the journals Neural Computation, Cognitive Science, and IEEE Expert, founder and director of the Center for Adaptive Systems, general chairman of the 1987 IEEE First International Conference on Neural Networks (ICNN); chief scientist of Hecht-Nielsen Neurocomputer Co (HNC); and one of four technical consultants to the national DARPA Neural Network Study. Dr. Grossberg has introduced key models and computational methods of content addressable memory, associative learning, competitive learning, competitive and cooperative decision making, vision and image processing, speech and language processing, adaptive pattern recognition, cognitive information processing, reinforcement learning, and adaptive sensory-motor control. He is author of 200 articles and books about neural networks, the latter including Neural Networks and Natural Intelligence (MIT Press), Neural Dynamics of Adaptive Sensory-Motor Control (with Michael Kuperstein; Pergamon Press), The Adaptive Brain, Volumes I and II, (Elsevier/North-Holland Press), Studies of Mind and Brain (Reidel Press), and the forthcoming Pattern Recognition by Self-Organizing Neural Networks (with Gail Carpenter).

GAIL CARPENTER is professor of mathematics and CNS, codirector of the CNS Graduate Program; 1989 vice president of the International Neural Network Society (INNS); organization chairman of the 1988 INNS annual meeting, session chairman at the 1989 and 1990 IEEE/INNS International Joint Conference on Neural Networks; one of four technical consultants to the national DARPA Neural Network Study; an editor of the journals Neural Networks, Neural Computation, and Neural Network Review; and a member of the scientific advisory board of HNC. She is a leading neural architect who has carried out advanced research in vision, nerve impulse generation (Hodgkin-Huxley equations), and complex biological rhythms. Dr Carpenter is especially well-known for her seminal work on developing the adaptive resonance theory architectures (ART 1, 2, and 3) for adaptive pattern recognition.

MICHAEL COHEN, associate professor of computer science and CNS, is a leading architect of neural networks for content addressable memory (Cohen-Grossberg model), vision (Feature Contour System), and speech (Masking Fields), an editor of Neural Networks, session chairman at the 1987 IEEE International Conference on Neural Networks and the 1989 IEEE/INNS International Joint Conference on Neural Networks; and a member of the DARPA Neural Network Study panel on Simulation/Emulation Tools and Techniques. He was trained at the Massachusetts Institute of Technology, Harvard University, and New York University, where he did research on transformational grammars, telecommunications, and image processing before beginning his distinguished work on neural networks at Boston University.

ENNIO MINGOLLA, assistant professor of psychology and CNS, is holder of one of the first patented neural network architectures for vision and image processing (Boundary Contour System), co-organizer of the Third Workshop on Human and Machine Vision in 1985, editor of the journals Neural Networks and Ecological Psychology; a member of the DARPA Neural Network Study panel on Adaptive Knowledge Processing, consultant to E. I. du Pont de Nemours, Inc.; session chairman for vision and image processing at the 1987 IEEE First International Conference on Neural Networks and the 1988 Annual INNS Meeting, and invited speaker at the 1990 IEEE/INNS International Joint Conference on Neural Networks.

DANIEL BULLOCK, assistant professor of psychology and CNS, is developer of neural network models for real-time adaptive sensory-motor control of arm movements and eye-arm coordination, notably the VITE and FLETE models for adaptive control of multi-joint trajectories; an editor of Neural Networks; session chairman for adaptive sensory-motor control and robotics at the 1987 IEEE First International Conference on Neural Networks and the 1988 Annual INNS Meeting, and invited speaker at the 1990 IEEE/INNS International Conference on Neural Networks. He is well-known for his research in cognitive and developmental psychology.

JOHN MERRILL, assistant professor of mathematics and CNS, is developing neural network models for adaptive pattern recognition, speech recognition, reinforcement learning, and adaptive timing in problem-solving behavior. He received his Ph D. in mathematics from the University of Wisconsin at Madison, and completed postdoctoral research in computer science and linguistics at Indiana University.

COURSE GUEST LECTURERS

FEDERICO FAGGIN, cofounder and president of Synaptics, Inc., received a doctoral degree in physics from the University of Padua, Italy, in 1965. In 1968 he joined the R & D laboratory of Fairchild Semiconductor in Palo Alto, California. At Fairchild he developed the Silicon Gate Technology: the first viable high-speed and high-density MOS process using a doped polycrystalline silicon gate electrode. The same year, Faggin also designed the first commercial circuit using Silicon Gate Technology. the 3708, an 8-bit analog multiplexer. Prior to leaving Fairchild, he was group leader in charge of the development of advanced process technologies. In 1970 he joined the Intel Corporation with the responsibility of designing what was to become the first microprocessor — the 4000-family, also called MCS-4. The product was introduced in the market in November 1971. Faggin was in charge of all of the microprocessor development activity at Intel from inception until October 1974, when he left the company to start Zilog, Inc. At Intel, Faggin and Hal Feeney designed the 8008, the first 8-bit microprocessor, introduced in 1972; later, Faggin conceived the 8080 and designed it with M. Shima. The 8080 was introduced in the market in 1974 and was the first high-performance 8-bit microprocessor. Before leaving Intel in 1974, Faggin was department manager with responsibility for all MOS design activity except for dynamic RAMs. At Zilog, Faggin conceived the Z80 microprocessor family and directed the design of the Z80-CPU. Faggin was cofounder, president, and CEO of Zilog from inception until the end of 1980. After a brief period as Group VP of Exxon Enterprises, Zilog's parent company, in 1981, Faggin started a new company in 1982 and became its president. This company, Cygnet Technologies, developed and introduced in the market a voice and data communication peripheral for the personal computer. Faggin is the author or coauthor of many technical papers and is inventor or co-inventor of many U.S and foreign patents. He is the recipient of the 1988 Marconi Fellowship Award for his contributions to the birth of the microprocessor.

ROBERT HECHT-NIELSEN, cofounder and Chairman of the Board of Directors of Hecht-Nielsen Corporation (HNC), is a pioneer in neurocomputer technology and the application of neural networks, and is a recognized leader in the field. Prior to the formation of HNC, he founded and managed the neurocomputer development and neural network applications at TRW (1983 - 1986) and Motorola (1979 - 1983). He has been active in neural network technology and neurocomputers since 1961. Dr. Hecht-Nielsen is a graduate of Arizona State University, where he was an NDEA Fellow, an ASU Fellow, and two-time chapter president of Pi Mu Epsilon, with B.S. (1971) and Ph.D. (1974) degrees in mathematics. He is currently a visiting lecturer in the Electrical Engineering Department at the University of California at San Diego. He is the author of more than twenty technical reports and papers on neurocomputers, neural networks, pattern recognition, signal processing algorithms and artificial intelligence. Hecht-Nielsen is a Brain and Behavioral Sciences Associate

MICHAEL I. JORDAN is an assistant professor of brain and cognitive sciences at the Massachusetts Institute of Technology. One of the key developers of the recurrent back propagation algorithms, Professor Jordan's research is concerned with learning in recurrent networks and with the use of networks as forward models in planning and control. His interest in interdisciplinary research on neural networks is founded in his training for a bachelor's degree in psychology, a master's degree in mathematics, and a doctoral degree in cognitive science in 1985 from the University of California at San Diego. He was a postdoctoral researcher in computer science at the University of Massachusetts-Amherst from 1986 to 1988 before assuming his present position at MIT.

Course Schedule

MAY 6, 1990

Registration, 1 - 5 p.m.

Reception, 5 - 8 p.m.

MAY 7, 1990

MORNING SESSION (PROFESSOR GROSSBERG), 8 - 10 A.M.

HISTORICAL OVERVIEW: Introduction to the binary, linear, and continuous-nonlinear streams of neural network research: McCulloch-Pitts, Rosenblatt, von Neumann; Anderson, Kohonen, Widrow; Hodgkin-Huxley, Hartline-Ratliff, Grossberg.

CONTENT ADDRESSABLE MEMORY. Classification and analysis of neural network models for absolutely stable CAM. Models include: Cohen-Grossberg, additive, shunting, Brain-State-In-A-Box, Hopfield, Boltzmann Machine, McCulloch-Pitts, masking field, bidirectional associative memory.

COOPERATIVE AND COMPETITIVE DECISION MAKING. Analysis of asynchronous variable-load parallel processing by shunting competitive networks; solution of noise-saturation dilemma, classification of feedforward networks: automatic gain control, ratio processing, Weber law, total activity normalization, noise suppression, pattern matching, edge detection, brightness constancy and constrast; automatic compensation for variable illumination or other background energy distortions; classification of feedback networks; influence of nonlinear feedback signals, notably sigmoid signals, on pattern transformation and memory storage, winner-take-all choices, partial memory compression, tunable filtering, quantization and normalization of total activity, emergent boundary segmentation; method of jumps for classifying globally consistent and inconsistent competitive decision schemes.

Coffee Break, 10 - 10:30 a.m.

MORNING SESSION (PROFESSOR GROSSBERG), 10:30 A.M. - 12:30 P.M.

ASSOCIATIVE LEARNING: Derivation of associative equations for short-term memory and long-term memory; overview and analysis of associative outstars, instars, computational maps, avalanches, counterpropagation nets, adaptive bidirectional associative memories; analysis of unbiased associative pattern learning by asynchronous parallel sampling channels, classification of associative learning laws.

Lunch at Wang Institute 12:30 - 1:30 p.m.

AFTERNOON SESSION (PROFESSORS CARPENTER AND MINGOLLA), 1:30 - 3:30 P.M.

COMBINATORIAL OPTIMIZATION PERCEPTRONS: Adeline, Madeline, delta rule, gradient descent, adaptive statistical predictor, nonlinear separability.

INTRODUCTION TO BACK PROPAGATION: Supervised learning of multidimensional nonlinear maps, NETtalk, image compression, robotic control.

Coffee Break 3:30 - 4 p.m.

AFTERNOON SESSION (PROFESSOR JORDAN), 4 - 6 P.M.

RECENT DEVELOPMENTS OF BACK PROPAGATION: This guest tutorial lecture will provide a systematic review of recent developments of the back propagation learning network, focusing especially on recurrent back propagation variations and applications to outstanding technological problems.

Dinner at Wang Institute, 6 - 7:30 p.m.

EVENING SESSION, 7:30 - 8:30 P.M.
DISCUSSIONS WITH TUTORS
INFORMAL PRESENTATIONS

MAY 8, 1990

MORNING SESSION (PROFESSOR GROSSBERG), 8 - 10 A.M.

ADAPTIVE PATTERN RECOGNITION: Adaptive filtering; contrast enhancement; competitive learning of recognition categories; adaptive vector quantization; self-organizing computational maps; statistical properties of adaptive weights; learning stability and causes of instability.

Coffee Break, 10 - 10:30 a.m.

MORNING SESSION (PROFESSORS CARPENTER AND GROSSBERG), 10:30 A.M. - 12:30 P.M.

INTRODUCTION TO ADAPTIVE RESONANCE THEORY: Absolutely stable recognition learning, role of learned top-down expectations; attentional priming; matching by 2/3 Rule; adaptive search; self-controlled hypothesis testing, direct access to globally optimal recognition code; control of categorical coarseness by attentional vigilance, comparison with relevant behavioral and brain data to emphasize biological basis of ART computations.

ANALYSIS OF ART 1: Computational analysis of ART 1 architecture for self-organized real-time hypothesis testing, learning, and recognition of arbitrary sequences of binary input patterns.

Lunch at Wang Institute, 12:30 - 1:30 p.m.

AFTERNOON SESSION (PROFESSOR CARPENTER), 1:30 - 3:30 P.M.

ANALYSIS OF ART 2: Computational analysis of ART 2 architecture for self-organized real-time hypothesis testing, learning, and recognition for arbitrary sequences of analog or binary input patterns.

ANALYSIS OF ART 3. Computational analysis of ART 3 architecture for self-organized real-time hypothesis testing, learning, and recognition within distributed network hierarchies, role of chemical transmitter dynamics in forming a memory representation distinct from short-term memory and long-term memory; relationships to brain data concerning neuromodulators and synergetic ionic and transmitter interactions.

Coffee Break, 3:30 - 4 p.m.

AFTERNOON SESSION (PROFESSOR CARPENTER), 4 - 6 P.M.

ANALYSIS OF ART 3, CONTINUED

SELF-ORGANIZATION OF INVARIANT PATTERN RECOGNITION CODES Computational analysis of self-organizing ART architectures for recognizing noisy imagery undergoing changes in position, rotation, and size.

NEOCOGNITRON: Recognition and completion of images by hierarchical bottom-up filtering and top-down attentive feedback.

Dinner at Wang Institute, 6 - 7:30 p.m.

EVENING SESSION, 7:30 - 8:30 P.M.
DISCUSSIONS WITH TUTORS
INFORMAL PRESENTATIONS

MAY 9, 1990

MORNING SESSION (PROFESSORS GROSSBERG AND MINGOLLA), 8 - 10 A.M.

VISION AND IMAGE PROCESSING Introduction to Boundary Contour System for emergent segmentation and Feature Contour System for filling-in after compensation for variable illumination; image compression, orthogonalization, and reconstruction; multidimensional filtering, multiplexing, and fusion.

Coffee Break 10 - 10:30 a.m.

MORNING SESSION (PROFESSORS GROSSBERG AND MINGOLLA), 10:30 - 12:30 P.M.

VISION AND IMAGE PROCESSING: Coherent boundary detection, regularization, self-scaling, and completion; compensation for variable illumination sources, including artificial sensors (infrared sensors, laser radars); filling-in of surface color and form, 3-D form from shading, texture, stereo, and motion; parallel, processing of static form and moving form; motion capture and induced motion, synthesis of static form and motion form representations.

Lunch at Wang Institute, 12:30 - 1:30 p.m.

AFTERNOON SESSION (PROFESSORS BULLOCK AND GROSSBERG), 1:30 - 3:30 P.M.

ADAPTIVE SENSORY-MOTOR CONTROL AND ROBOTICS Overview of recent progress in adaptive sensory-motor control and related robotics research. Reaching, grasping, and transporting objects of variable mass and form under visual guidance in a cluttered environment will be used as a target behavioral competence to clarify subproblems of real-time adaptive sensory-motor control. The balance of the tutorial will be spent detailing neural network modules that solve various subproblems. Topics include: Self-organizing networks for real-time control of eye movements, arm movements, and eye-arm coordination, learning of invariant body-centered target position maps; learning of intermodal associative maps; real-time trajectory formation; adaptive vector encoders; circular reactions between action and sensory feedback, adaptive control of variable speed movements, varieties of error signals; supportive behavioral and neural data.

Coffee Break, 3:30 - 4 p.m.

AFTERNOON SESSION (PROFESSORS BULLOCK AND COHEN), 4 - 6 P.M.

ADAPTIVE SENSORY-MOTOR CONTROL AND ROBOTICS: Inverse kinematics; automatic compensation for unexpected perturbations; independent adaptive control of force and position, adaptive gain control by cerebellar learning; position-dependent sampling from spatial maps, predictive motor planning and execution.

SPEECH PERCEPTION AND PRODUCTION. Hidden Markov models, self organization of speech perception and production codes, eighth nerve Average Localized Synchrony Response; phoneme recognition by back propagation, time delay networks, and vector quantization.

Dinner at Wang Institute, 6 - 7:30 p.m.

EVENING SESSION, 7:30 - 8:30 P.M.
DISCUSSIONS WITH TUTORS
INFORMAL PRESENTATIONS

MAY 10, 1990

MORNING SESSION (PROFESSORS COHEN AND GROSSBERG), 8 - 10 A.M.

SPEECH PERCEPTION AND PRODUCTION. Disambiguation of coarticulated vowels and consonants; dynamics of working memory; multiple-scale adaptive coding by masking fields; categorical perception; phonemic restoration; contextual disambiguation of speech tokens; resonant completion and grouping of noisy variable-rate speech streams.

Coffee Break, 10 - 10:30 a.m.

MORNING SESSION (PROFESSORS GROSSBERG AND MERRILL), 10:30 A.M. - 12:30 P.M.

REINFORCEMENT LEARNING AND PREDICTION. Recognition learning, reinforcement learning, and recall learning are the 3 R's of neural network learning. Reinforcement learning clarifies how external events interact with internal organismic requirement to trigger learning processes capable of focusing attention upon and generating appropriate actions toward motivationally desired goals. A neural network model will be derived to show how reinforcement learning and recall learning can self-organize in response to asynchronous series of significant and irrelevant events. These mechanisms also control selective forgetting of memories that are no longer predictive, adaptive timing of behavioral responses, and self-organization of goal-directed problem solvers.

Lunch at Wang Institute, 12:30 - 1:30 p.m.

AFTERNOON SESSION (PROFESSORS GROSSBERG AND MERRILL), 1:30 - 3:30 P.M.

REINFORCEMENT LEARNING AND PREDICTION: Analysis of drive representations, adaptive critics, conditioned reinforcers, role of motivational feedback in focusing attention on predictive data, attentional blocking and unblocking; adaptively timed problem solving; synthesis of perception, recognition, reinforcement, recall, and robotics mechanisms into a total neural architecture, relationship to data about hypothalamus, hippocampus, neocortex, and related brain regions.

Coffee Break, 3:30 - 4 p.m.

AFTERNOON SESSION (DR. HECHT-NIELSEN), 4 - 6 P.M.

RECENT DEVELOPMENTS IN THE NEUROCOMPUTER INDUSTRY: This guest tutorial will provide an overview of the growth and prospects of the burgeoning neurocomputer industry by one of its most important leaders.

Dinner at Wang Institute, 6 - 7:30 p.m.

EVENING SESSION, 7:30 - 8:30 P.M.
DISCUSSIONS WITH TUTORS
INFORMAL PRESENTATIONS

MAY 11, 1990

MORNING SESSION (DR. FAGGIN), 8 - 10 A.M.

VLSI IMPLEMENTATION OF NEURAL NETWORKS — THE PROBLEM: This is a four-hour self-contained tutorial on the application and development of VLSI techniques for creating compact real-time chips embodying neural network designs for applications in technology. Review of neural networks from a hardware implementation perspective; hardware requirements and alternatives; dedicated digital implementation of neural networks.

Coffee Break, 10 - 10:30 a.m.

MORNING SESSION (DR. FAGGIN), 10:30 A.M. - 12:30 P.M.

VLSI IMPLEMENTATION OF NEURAL NETWORKS — A NOVEL APPROACH: Neuromorphic design methodology using VLSI CMOS technology; applications and performance of neuromorphic implementation; comparison of neuromorphic and digital hardware; future prospectus.

Lunch at Wang Institute, 12:30 - 1:30 p.m.

End of the course.

Neural Networks for Automatic Target Recognition

May 11 - 13, 1990

This research conference at the cutting edge of neural network science and technology will bring together leading experts in academe, government, and industry to present their results on automatic target recognition in invited lectures and contributed posters. Automatic target recognition is a key process in systems designed for vision and image processing, speech, and time series prediction, adaptive pattern recognition, and adaptive sensory-motor control and robotics. It is one of the areas emphasized by the DARPA Neural Networks Program, and has attracted intense research activities around the world.

Call for Papers — ATR Poster Session: A featured poster session on ATR neural network research will be held on May 12, 1990. Attendees who wish to present a poster should submit three copies of an abstract (one single-spaced page), postmarked by March 1, 1990, for refereeing. Include with the abstract the name, address, and telephone number of the corresponding author. Mail to: ATR Poster Session, Neural Networks Conference, Wang Institute of Boston University, 72 Tyng Road, Tyngsboro, MA 01879. Authors will be informed of abstract acceptance by March 31, 1990.

CONFERENCE PROGRAM

MAY 11, 1990

REGISTRATION 1 - 5 P.M.

RECEPTION 3 - 5 P.M.

EVENING SESSION 5 - 7:30 P.M.

DR. BARBARA YOON, DARPA
"DARPA Artificial Neural Networks Technology Program: Automatic Target Recognition"

DR. JOE BROWN, MARTIN MARIETTA
"Multi-Sensor ATR Using Neural Nets"

DR. ROBERT HECHT-NIELSEN, HNC
"Spatiotemporal Attention Focusing by Expectation Feedback"

(Participants are on their own for dinner.)

MAY 12, 1990

MORNING SESSION
8 A.M. - 12 NOON

PROFESSOR ALEX WAIBEL, CARNEGIE-MELLON UNIVERSITY
"Patterns, Sequences, and Variability: Advances in Connectionist Speech Recognition"

DR. CHRISTOPHER SCOFIELD, NESTOR, INC.
"Neural Network Automatic Target Recognition by Active and Passive Sonar Signals"

Coffee Break

PROFESSOR STEPHEN GROSSBERG, BOSTON UNIVERSITY
"Recent Results on Self-Organizing ATR Networks"

PROFESSOR GAIL CARPENTER, BOSTON UNIVERSITY
"Target Recognition by Adaptive Resonance: ART for ATR"

Lunch 12 noon - 1 p.m.

AFTERNOON SESSION 1 - 4 P.M.

DR. KEN JOHNSON, HUGHES AIRCRAFT COMPANY
"The Application of Neural Networks to the Acquisition and Tracking of Maneuvering Tactical Targets in High Clutter IR Imagery"

DR. ALLEN WAXMAN, MIT LINCOLN LAB
"Invariant Learning and Recognition of 3D Objects from Temporal View Sequences"

DR. PAUL KOLODZY, MIT LINCOLN LAB
"A Multi-Dimensional ATR System"

Coffee Break

POSTER SESSION 4 - 7 P.M.

Dinner at Wang Institute 7 - 8 p.m.

MAY 13, 1990

MORNING SESSION
8 A.M. - 1 P.M.

PROFESSOR NABIL FARHAT, UNIVERSITY OF PENNSYLVANIA
"Bifurcating Networks for Target Recognition"

DR. FRED WEINGARD, BOOZ-ALLEN AND HAMILTON
"Current Status and Results of Two Major Government Programs in Neural Network-Based ATR"

Coffee Break

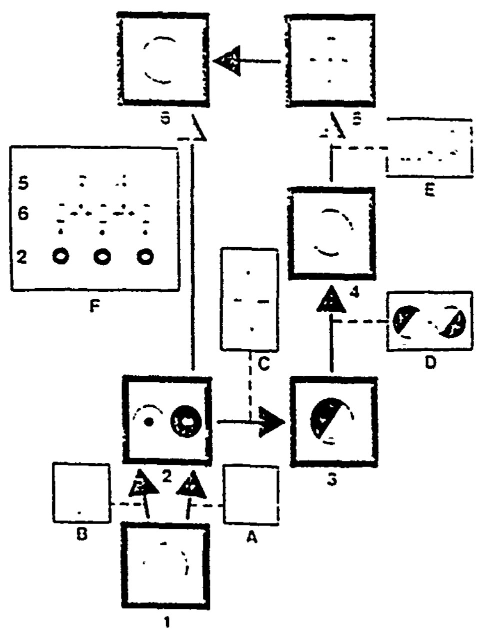
DR. MICHAEL KUPERSTEIN, NEUROGEN
"Adaptive Sensory Motor Coordination Using the INFANT Controller"

DR. YANN LE CUN, AT & T LABORATORIES
"Structured Back Propagation Networks for Handwriting Recognition"

DR. STEVEN SIMMES, SAIC
"Massively Parallel Approaches to Automatic Target Recognition"

Discussion

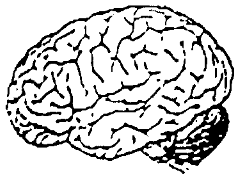
End of the research conference.



BOSTON UNIVERSITY

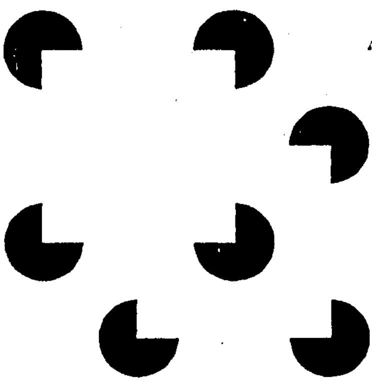
A World Leader in Neural Network Research and Technology
presents

Two Major Events on the Cutting Edge

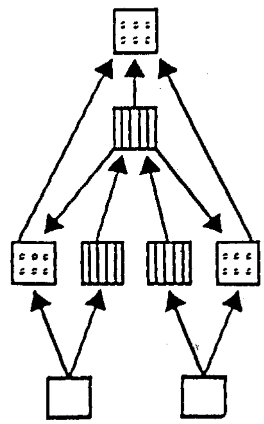


Neural Networks: From Foundations to Applications

May 5-10, 1991



A self-contained systematic course
by leading neural architects.



Neural Networks for Vision and Image Processing

May 10-12, 1991

An international research conference presenting INVITED and CONTRIBUTED papers, herewith solicited, on one of the most active research topics in science and technology today.

Each event offers a unique opportunity to master vital information.
Both events together provide a week of rare intellectual
excitement and usefulness.

Special student registration rates are available.

Sponsored by Boston University's Wang Institute, Center for Adaptive Systems, and Graduate Program in Cognitive and Neural Systems with partial support from the Air Force Office of Scientific Research.

Neural Networks: From Foundations to Applications

May 5 – 10, 1991

This self-contained systematic five-day course is based on the graduate curriculum in the technology, computation, mathematics, and biology of neural networks developed at the renowned Center for Adaptive Systems (CAS) and the graduate program in Cognitive and Neural Systems (CNS) of Boston University. This year's curriculum refines and updates the successful course held at the Wang Institute in May 1990. The course will be taught by CAS/CNS faculty, as well as by distinguished guest lecturers at the beautiful and superbly equipped campus of the Wang Institute. An extraordinary range and depth of models, methods, and applications will be presented with ample opportunity for interaction with the lecturers and other participants at the daily discussion sections, meals, receptions, and breaks that are included with registration. At the 1990 course, participants came from twenty countries and thirty-five states of the United States.

COURSE FACULTY FROM BOSTON UNIVERSITY

STEPHEN GROSSBERG, Wang Professor of CNS, as well as professor of mathematics, psychology, and biomedical engineering, is one of the world's leading neural network pioneers and most versatile neural architects. The founder and 1988 president of the International Neural Network Society (INNS), he is also founder and coeditor in chief of the INNS journal, *Neural Networks*; an editor of the journals *Neural Computation*, *Cognitive Science*, and *IEEE Expert*; founder and director of the Center for Adaptive Systems; general chairman of the 1987 IEEE First International Conference on Neural Networks (ICNN), and one of four technical consultants to the National DARPA Neural Network Study. Dr. Grossberg has introduced key models and computational methods of content addressable memory, associative learning, competitive learning, competitive and cooperative decision making, vision and image processing, speech and language processing, adaptive pattern recognition, cognitive information processing, reinforcement learning, and adaptive sensory-motor control. He is author of 200 articles and books about neural networks.

GAIL CARPENTER is a professor of mathematics and CNS; codirector of the CNS graduate program; 1989 vice president of the International Neural Network Society (INNS); organization chairman of the 1988 INNS annual meeting; session chairman at the 1989 and 1990 IEEE. INNS International Joint Conference on Neural Networks; one of four technical consultants to the National DARPA Neural Network Study; and an editor of the journals *Neural Networks*, *Neural Computation*, and *Neural Network Review*. She is a leading neural architect who has carried out advanced research in vision, nerve impulse generation (Hodgkin-Huxley equations), and complex biological rhythms. Dr. Carpenter is especially well-known for her seminal work on developing the adaptive resonance theory architectures (ART 1, 2, and 3) for adaptive pattern recognition for which she and Dr. Grossberg hold a series of patents.

MICHAEL COHEN, associate professor of computer science and CNS, is a leading architect of neural networks for content addressable memory (Cohen-Grossberg model), vision (Feature Contour System), and speech (Masking Fields); editor of *Neural Networks*, session chairman at the 1987 IEEE International Conference on Neural Networks and the 1989 IEEE/INNS International Joint Conference on Neural Networks; and member of DARPA Neural Network Study Panel on Simulation/Emulation Tools and Techniques. He was trained at the Massachusetts Institute of Technology, Harvard University, and New York University, where he did research on transformational grammars, telecommunications, and image processing before beginning his distinguished work on neural networks at Boston University.

ENNIO MINGOLLA, an assistant professor of psychology and CNS, is co-inventor with Dr. Grossberg of one of the first patented neural network architectures for visi n and image processing (Boundary Contour System); co-organizer of the Third Workshop on Human and Machine Vision in 1985; editor of the journals *Neural Networks* and *Ecological Psychology*, a member of the DARPA Neural Network Study Panel on Adaptive Knowledge Processing, session chairman for Vision and Image Processing at the 1987 IEEE First International Conference on Neural Networks and the 1988 Annual INNS Meeting; and invited speaker at the 1990 IEEE/INNS International Joint Conference on Neural Networks and the 1990 Neural Information Processing Symposium (NIPS).

DANIEL BULLOCK, associate professor of psychology and CNS, is developer of neural network models for real-time adaptive sensory-motor control of arm movements and eye-arm coordination, notably the VITE and FLETE Models for adaptive control of multi-joint trajectories; editor of *Neural Networks*; session chairman for adaptive sensory-motor control and robotics at the 1987 IEEE First International Conference on neural networks and the 1988 Annual INNS Meeting; and invited speaker at the 1990 IEEE/INNS International Joint Conference on Neural Networks and the 1990 International Symposium on Neural Networks for Sensory and Motor Systems. He is also well-known for his research in cognitive and developmental psychology.

JOHN MERRILL, assistant professor of mathematics and CNS, is developing neural network models for adaptive pattern recognition, speech recognition, reinforcement learning, and adaptive timing in problem solving behavior, after having received his Ph.D. in mathematics from the University of Wisconsin at Madison, and completed postdoctoral research in computer science and linguistics at Indiana University.

COURSE GUEST LECTURERS

FEDERICO FAGGIN, cofounder and president of Synaptics, Inc., received a doctoral degree in physics from the University of Padua, Italy, in 1965. In 1968 he joined the R & D laboratory of Fairchild Semiconductor in Palo Alto, California, where he developed the Silicon Gate Technology. In 1970, he joined the Intel Corporation, where he designed the first microprocessor. With Hal Feeney, he designed the first 8-bit microprocessor, and with M. Shima, the first high-performance 8-bit microprocessor. Dr. Faggin was cofounder, president, and CEO, from its inception until the end of 1980, at Zilog where he conceived the Z80 microprocessor family and directed design of the Z80-CPU. He started Cygnet Technologies in 1982 and became its president. Dr. Faggin is the author or coauthor of many technical papers and is inventor or coinventor of many U.S. and foreign patents. He is the recipient of the 1988 Marconi Fellowship Award for his work on the microprocessor.

ROBERT HECHT-NIELSEN, cofounder and chairman of the board of directors of Hecht-Nielsen Corporation (HNC), is a pioneer in neurocomputer technology and the application of neural networks. Prior to the formation of HNC, he founded and managed the neurocomputer development and neural network applications at TRW (1983–1986) and Motorola (1979–1983). Dr. Hecht-Nielsen is a graduate of Arizona State University with B.S. (1971) and Ph.D. (1974) degrees in mathematics. He is currently a visiting lecturer at the Electrical Engineering Department of the University of California at San Diego and the author of a book and many technical reports and papers on neurocomputers, neural networks, pattern recognition, signal processing algorithms, and intelligence.

MICHAEL I. JORDAN, assistant professor of brain and cognitive sciences at the Massachusetts Institute of Technology, is one of the key developers of the recurrent back propagation algorithms. Dr. Jordan's research is concerned with learning in recurrent networks and with the use of networks as forward models in planning and control. His interest in interdisciplinary research on neural networks is founded in his training for a bachelor's degree in psychology, a master's degree in mathematics, a doctoral degree in cognitive science, and postdoctoral research in computer science, and has continued in his present position at the Massachusetts Institute of Technology.

ANDREW G. BARTO is associate professor of computer and information science at the University of Massachusetts at Amherst. He received a B.S. in mathematics (1970) and a Ph.D. in computer science (1975) from the University of Michigan with a thesis concerning cellular automata. Since 1977, Dr. Barto has developed neural network learning algorithms that do not require reliable and detailed instructions from a knowledgeable environment. At present, he is exploring links between research in animal behavior, adaptive and optimal control, and learning methods for biologically plausible networks.

ALEX WAIBEL is a research computer scientist in the Computer Science Department and the Center for Machine Translation of Carnegie Mellon University. He received a B.S. (1979) from the Massachusetts Institute of Technology, and an M.S. in electrical engineering and computer science (1980) and Ph.D. in computer science (1986) from Carnegie Mellon University. In 1987, 88 he was a research scientist at the ATR Telephony Research Laboratories in Osaka, Japan, where he started and codirected a group for neural network based speech recognition. Dr. Waibel has published more than forty papers on speech recognition and synthesis, neurocomputing, machine learning, and machine translation.

Course Schedule

MAY 5, 1991

Registration 4 – 6 p.m.

Reception 5 – 8 p.m.

MAY 6, 1991

MORNING SESSION (PROFESSOR GROSSBERG), 8 – 10 A.M.

HISTORICAL OVERVIEW: Introduction to the binary, linear, and continuous-nonlinear streams of neural network research: McCulloch-Pitts, Rosenblatt, von Neumann; Anderson, Kohonen, Widrow; Hodgkin-Huxley, Hartline-Ratliff, Grossberg.

COOPERATION AND COMPETITION: Analysis of asynchronous variable-load parallel processing by cooperative-competitive networks; solution of noise-saturation dilemma; classification of feedforward networks: automatic gain control, ratio processing, Weber law, total activity normalization, noise suppression, pattern matching, edge detection, brightness constancy and contrast; automatic compensation for variable illumination or other background energy distortions; classification of feedback networks: influence of nonlinear feedback signals, notably sigmoid signals, on pattern transformation and memory storage, winner-take-all choices, partial memory compression, tunable filtering, quantization and normalization of total activity, visual short-term memory, behavioral contrast, working memory for temporally ordered events, synchronous oscillations in neural coding.

CONTENT ADDRESSABLE MEMORY: Classification and analysis of neural network models for absolutely stable CAM. Models include: Cohen-Grossberg, additive, shunting, Brain-State-In-A-Box, Hopfield, Boltzmann Machine, McCulloch-Pitts, masking field, bidirectional associative memory.

Coffee Break 10 – 10:30 a.m.

MORNING SESSION (PROFESSOR GROSSBERG), 10:30 A.M. – 12:30 P.M.

CONTENT ADDRESSABLE MEMORY, continued

ASSOCIATIVE LEARNING: Derivation of associative equations for short-term memory and long-term memory. Overview and analysis of associative outstars, instars, computational maps, avalanches, real-time learning of temporally ordered lists. Analysis of unbiased associative pattern learning by asynchronous parallel sampling channels. Classification of associative learning laws.

Lunch at Wang Institute, 12:30 – 1:30 p.m.

AFTERNOON SESSION (PROFESSORS CARPENTER, GROSSBERG, AND MINGOLLA), 1:30 – 3:30 P.M.

ASSOCIATIVE LEARNING, continued

NEOCOGNITRON: Recognition and completion of images by a hierarchy of bottom-up adaptive filters and top-down attentive feedback.

PERCEPTRONS: Delta rule, gradient descent, adaptive statistical predictor, nonlinear separability, Adaline, Madaline.

INTRODUCTION TO BACK PROPAGATION: Supervised learning of multidimensional nonlinear maps.

Coffee Break, 3:30 – 4 p.m.

AFTERNOON SESSION (PROFESSOR JORDAN), 4 – 6 P.M.

RECENT DEVELOPMENTS OF BACK PROPAGATION: Review of recent developments of the back propagation learning network, especially focusing on recurrent back propagation variations and applications to outstanding technological problems.

Dinner at Wang Institute, 6 – 7:15 p.m.

EVENING SESSION, 7:15 – 8:30 P.M.
DISCUSSIONS WITH TUTORS AND INFORMAL PRESENTATIONS

MAY 7, 1991

MORNING SESSION (PROFESSORS GROSSBERG AND MINGOLLA), 8 – 10 A.M.

ADAPTIVE PATTERN RECOGNITION: Adaptive filtering; derivation and analysis of instar avalanches, competitive learning models, and 3-level universal associative maps; adaptive vector quantization; self-organizing feature maps; statistical properties of adaptive weights; learning stability and causes of instability; applications to cortical feature maps and travelling salesman problem.

Coffee Break, 10 – 10:30 a.m.

MORNING SESSION (PROFESSORS CARPENTER AND GROSSBERG), 10:30 A.M. – 12:30 P.M.

INTRODUCTION TO ADAPTIVE RESONANCE THEORY: Absolutely stable recognition learning; role of learned top-down expectations; attentional priming; matching by 2/3 Rule; adaptive search; self-controlled hypothesis testing; direct access to globally optimal recognition code; control of categorical coarseness by attentional vigilance; comparison with relevant behavioral and brain data to emphasize biological basis of ART computations.

ANALYSIS OF ART 1: Computational analysis of ART 1 architecture for self-organized real-time hypothesis testing, learning, and recognition of arbitrary sequences of binary input patterns.

Lunch at Wang Institute, 12:30 – 1:30 p.m.

AFTERNOON SESSION (PROFESSOR CARPENTER), 1:30 – 3:30 P.M.

ANALYSIS OF ART 2: Computational analysis of ART 2 architecture for self-organized real-time hypothesis testing, learning, and recognition for arbitrary sequences of analog or binary input patterns.

ANALYSIS OF ART 3: Computational analysis of ART 3 architecture for self-organized real-time hypothesis testing, learning, and recognition within distributed network hierarchies; role of chemical transmitter dynamics in forming a medium-term memory representation distinct from short-term memory and long-term memory; relationships to brain data concerning neuromodulators and synergetic ionic and transmitter interactions.

Coffee Break, 3:30 – 4 p.m.

AFTERNOON SESSION (PROFESSOR CARPENTER), 4 – 6 P.M.

PREDICTIVE ART: Design of self-organizing systems capable of modifying recognition codes in real-time based upon their predictive success or failure, such that very different inputs may learn the same prediction, yet similar inputs may learn different predictions. ARTMAP applications.

SELF-ORGANIZATION OF INVARIANT PATTERN RECOGNITION CODES: Computational analysis of self-organizing ART architectures for recognizing noisy imagery undergoing changes in position, rotation, and size.

Dinner at Wang Institute, 6 – 7:15 p.m.

EVENING SESSION, 7:15 – 8:30 P.M.
DISCUSSIONS WITH TUTORS AND INFORMAL PRESENTATIONS

MAY 8, 1991

MORNING SESSION (PROFESSORS GROSSBERG AND MINGOLLA), 8 - 10 A.M.

VISION AND IMAGE PROCESSING: Introduction to central problems of biological vision; principles of complementarity, uncertainty, symmetry, and resonance in contemporary vision theory; derivation and analysis of the Boundary Contour System (BCS) for emergent boundary segmentation of edges; texture segmentation; brightness perception; illusory contours; 3-D figure-ground separation; processing of artificial sensor data (infrared, laser radar, magnetic resonance); neurobiological correlates.

Coffee Break, 10 – 10:30 a.m.

MORNING SESSION, (PROFESSORS GROSSBERG AND MINGOLLA), 10:30 - 12:30 P.M.

VISION AND IMAGE PROCESSING: Development of a unified theory of 3-D form and motion perception; derivation and analysis of a Motion BCS for solving the global motion segmentation problem; analysis of the different perceptual geometries of static and motion vision (opposite orientations differ by 90°, motion directions by 180°); tradeoff between resonance and reset to achieve coherent motion segmentation without massive perceptual smearing; unified explanations of classical and recent psychophysical data about short-range and long-range apparent motion, motion capture, induced motion, motion aftereffects; comparison between motion and attention; neurobiological correlates.

Lunch at Wang Institute, 12:30 – 1:30 p.m.

AFTERNOON SESSION, (PROFESSORS BULLOCK AND GROSSBERG), 1:30 - 3:30 P.M.

ADAPTIVE SENSORY-MOTOR CONTROL AND ROBOTICS: Overview of recent progress in adaptive sensory-motor control and related robotics research. Reaching, grasping, and transporting objects of variable mass and form under visual guidance in a cluttered environment will be used as a target behavioral competence to clarify subproblems of real-time adaptive sensory-motor control; self-organization of reactive and planned eye movements; universal adaptive gain control by cerebellar learning; networks for variable-speed control of multi-joint arm and speech articulator trajectories; self-organization of trajectory control parameters in real-time via rhythmic random sampling of the workspace; analysis of behavioral and neural data about human and monkey arm movements; introduction to the Vector Associative Map (or VAM) model for autonomous, real-time error based learning of multidimensional maps; VAM Cascades for spatial orientation and spatial-to-motor mapping.

Coffee Break, 3:30 – 4 p.m.

AFTERNOON SESSION, (PROFESSORS BULLOCK AND GROSSBERG), 4 - 6 P.M.

ADAPTIVE SENSORY-MOTOR PLANNING AND CONTROL: Self-organization of a body-centered representation of 3-D space, self-organization of planned sequences of motion actions, as in handwriting, at any realizable positions and sizes in the workspace; planned performance from memory and under visual guidance, flexible use of tools of variable length; inverse kinematics; automatic compensation for unexpected perturbations; independent adaptive control of force and position by spinal circuits; adaptive control of position-dependent moment arms and motor plant nonlinearities by cerebellar learning; triphasic bursts during rapid movement and breaking.

Dinner at Wang Institute, 6 – 7:15 p.m.

EVENING SESSION, 7:15 - 8:30 P.M.
DISCUSSIONS WITH TUTORS AND INFORMAL PRESENTATIONS

MAY 9, 1991

MORNING SESSION (PROFESSORS COHEN, GROSSBERG AND WAIBEL), 8 - 10 A.M.

SPEECH PERCEPTION AND PRODUCTION: Hidden Markov models; self organization of speech perception and production codes; phoneme recognition by back propagation; time delay networks; learned vector quantization; LR parsers; dynamic programming and Viterbi alignment; disambiguation of coarticulated vowels and consonants; dynamics of working memory; multiple-scale adaptive coding by masking fields; categorical perception; phonemic restoration; contextual disambiguation of speech tokens; resonant completion and grouping of noisy variable-rate speech streams.

Coffee Break, 10 – 10:30 a.m.

MORNING SESSION (PROFESSOR GROSSBERG), 10:30 A.M. - 12:30 P.M.

SPEECH PERCEPTION AND PRODUCTION, continued

REINFORCEMENT LEARNING AND PREDICTION: Recognition learning, reinforcement learning, and recall learning are the 3 R's of neural network learning. Reinforcement learning clarifies how external events interact with internal organismic requirements to trigger learning processes capable of focusing attention upon and generating appropriate actions toward motivationally desired goals. A neural network model will be derived to show how reinforcement learning and recall learning can self-organize in response to asynchronous series of significant and irrelevant events. These mechanisms also control selective forgetting of memories that are no longer predictive, adaptive timing of behavioral responses, and self-organization of goal-directed problem solvers.

Lunch at Wang Institute, 12:30 – 1:30 p.m.

AFTERNOON SESSION, (PROFESSORS BARTO, GROSSBERG, AND MERRILL), 1:30 - 3:30 P.M.

REINFORCEMENT LEARNING AND PREDICTION. Analysis of drive representations, adaptive critics, conditioned reinforcers, role of motivational feedback in focusing attention on predictive data; attentional blocking and unblocking; adaptively timed problem solving; gated dipole and other opponent processes; synthesis of perception, recognition, reinforcement, recall, and robotics mechanisms into a total neural architecture; neurobiological correlates.

Coffee Break, 3:30 – 4 p.m.

AFTERNOON SESSION, (DR. HECHT-NIELSEN), 4 - 6 P.M.

RECENT DEVELOPMENTS IN THE NEUROCOMPUTER INDUSTRY: Overview of the growth, recent developments, and prospects of the burgeoning neurocomputer industry.

Dinner at Wang Institute, 6 – 7:15 p.m.

EVENING SESSION, 7:15 - 8:30 P.M.
DISCUSSIONS WITH TUTORS AND INFORMAL PRESENTATIONS

MAY 10, 1991

MORNING SESSION
(DR. FAGGIN), 8 - 10 A.M.

VLSI IMPLEMENTATION OF NEURAL NETWORKS — THE PROBLEM: Application and development of VLSI techniques for creating compact real-time chips embodying neural network designs for applications in technology. Review of neural networks from a hardware implementation perspective; hardware requirements and alternatives; dedicated digital implementation of neural networks.

Coffee Break, 10 – 10:30 A.M.

MORNING SESSION (DR. FAGGIN)
10:30 A.M. - 12:30 P.M.

VLSI IMPLEMENTATION OF NEURAL NETWORKS — A NOVEL APPROACH: Neuromorphic design methodology using VLSI CMOS technology; applications and performance of neuromorphic implementation; comparison of neuromorphic and digital hardware; future prospectus.

Lunch at Wang Institute, 12:30 – 1:30 P.M.

End of the course.

Neural Networks for Vision and Image Processing

May 10 – 12, 1991

This international research conference on a topic at the cutting edge of science and technology will bring together leading experts in academe, government, and industry to present their results on vision and image processing, in invited lectures and contributed posters. Topics range from visual neurobiology and psychophysics through computational modelling to technological applications. Vision and image processing is one of the areas emphasized by the DARPA Neural Networks Program, and has attracted intense research activities around the world.

CALL FOR PAPERS — VIP POSTER SESSION: A featured poster session on neural network research related to vision and image processing will be held on May 11, 1991. Attendees who wish to present a poster should submit three copies of an abstract (one single-spaced page), postmarked by March 1, 1991, for refereeing. Include with the abstract the name, address, and telephone number of the corresponding author. Mail to: Poster Session, Neural Networks Conference, Wang Institute of Boston University, 72 Tyng Road, Tyngsboro, MA 01879. Authors will be informed of abstract acceptance by March 31, 1991.

CONFERENCE PROGRAM

MAY 10, 1991

REGISTRATION, 2 – 5 P.M.

RECEPTION, 3 – 5 P.M.

EVENING SESSION, 5 – 7:30 P.M.

5 – 5:50 p.m.
PROFESSOR JOHN DAUGMAN, CAMBRIDGE UNIVERSITY
"High-Confidence Personal Identification System Built from Quadrature Neural Filter"

5:50 — 6:40 p.m.
PROFESSOR DAVID CASASENT, CARNEGIE MELLON UNIVERSITY
"CMU Hybrid Optical/Digital Neural Net for Scene Analysis"

6:40 – 7:30 p.m.
DR. ROBERT HECHT-NIELSEN, HNC
"Neurocomputers for Image Analysis"

(Dinner not included with this evening's session.)

MAY 11, 1991

MORNING SESSION 8 A.M. – 12:40 P.M.

8 – 8:50 a.m.
PROFESSOR V. S. RAMACHANDRAN, UNIVERSITY OF CALIFORNIA, SAN DIEGO
"Interactions Between 'Channels' Concerned with the Perception of Motion, Depth, Color, and Form"

8:50 – 9:40 a.m.
PROFESSOR STEPHEN GROSSBERG, BOSTON UNIVERSITY
"A Neural Network Architecture for 3-D Vision and Figure-Ground Separation"

9:40 – 10:30 a.m.
PROFESSOR ENNIO MINGOLLA, BOSTON UNIVERSITY
"A Neural Network Architecture for Visual Motion Segmentation"

Coffee Break, 10:30 – 11 a.m.

11 – 11:50 a.m.
PROFESSOR GEORGE SPERLING, NEW YORK UNIVERSITY
"Two Systems of Visual Processing"

11:50 – 12:40 p.m.
DR. ROBERT DESIMONE, NATIONAL INSTITUTE OF MENTAL HEALTH
"Attentional Control of Visual Perception: Cortical and Subcortical Mechanisms"

Lunch at Wang Institute, 12:40 – 2 p.m.

AFTERNOON SESSION, 2 – 4:30 P.M.

2 – 2:50 p.m.
PROFESSOR GAIL CARPENTER, BOSTON UNIVERSITY
"Neural Network Architectures for Attentive Learning, Recognition and Prediction"

2:50 – 3:40 p.m.
DR. RALPH LINSKER, IBM T. J. WATSON RESEARCH CENTER
"New Approaches to Network Learning and Optimization"

3:40 – 4:30 p.m.
PROFESSOR STUART ANSTIS, UNIVERSITY OF TORONTO
"My Recent Research on Motion Perception"

POSTER SESSION AND REFRESHMENTS, 4:30 – 7:30 P.M.

Dinner at Wang Institute, 7:30 – 8:45 p.m.

MAY 12, 1991

MORNING SESSION 8 A.M. – 1 P.M.

8 – 8:50 a.m.
PROFESSOR JACOB BECK, UNIVERSITY OF OREGON
"Preattentive Visual Processing"

8:50 – 9:40 a.m.
PROFESSOR JAMES TODD, BRANDEIS UNIVERSITY
"Neural Analysis of Motion"

9:40 – 10:30 a.m.
DR. ALLEN M. WAXMAN, MIT LINCOLN LAB
"Neurodynamics of Real-Time Image Velocity Extraction"

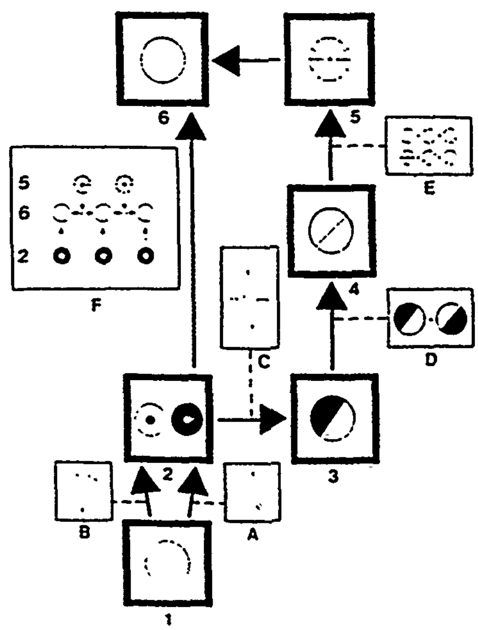
Coffee Break, 10:30 – 11 a.m.

11 – 11:50 a.m.
PROFESSOR ERIC SCHWARTZ, NEW YORK UNIVERSITY
"Biologically Motivated Machine Vision"

11:50 – 12:40 p.m.
PROFESSOR ALEX PENTLAND, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
"The Optimal Observer: Design of a Dynamically Responding Visual System"

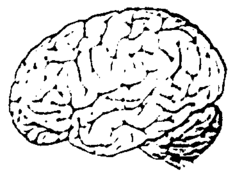
Discussion

End of the research conference.



BOSTON UNIVERSITY

NEURAL NETWORK COURSES AND CONFERENCE



Course 1: Introduction and Foundations

May 9–12, 1992

A systematic introductory course on neural networks

Course 2: Research and Applications

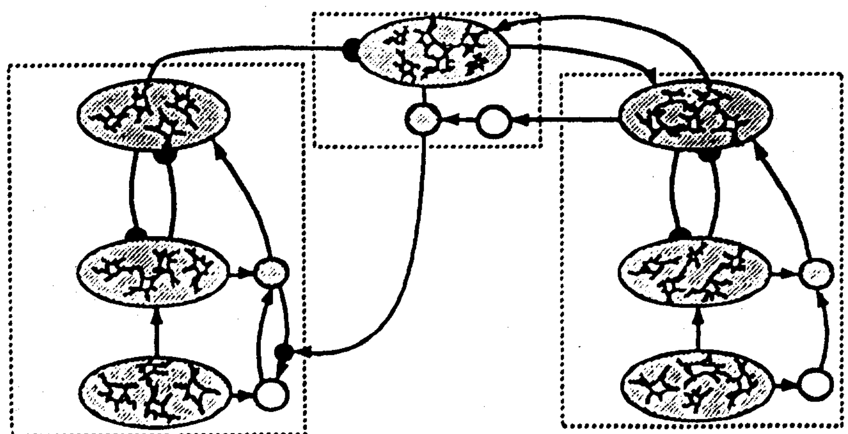
May 12–14, 1992

Eight tutorials on current research and applications

Conference: Neural Networks for Learning, Recognition, and Control

May 14–16, 1992

An international research conference presenting INVITED and CONTRIBUTED papers



Sponsored by Boston University's Wang Institute, Center for Adaptive Systems, and Department of Cognitive and Neural Systems, with partial support from the Air Force Office of Scientific Research

Neural Network Courses

MAY 9–14, 1992

This self-contained, systematic, five-day course is based on the graduate curriculum in the technology, computation, mathematics, and biology of neural networks developed at the Center for Adaptive Systems (CAS) and the Department of Cognitive and Neural Systems (CNS) of Boston University. This year's curriculum refines and updates the successful course held at the Wang Institute of Boston University in May 1990 and 1991. A new two-course format permits both beginners and researchers to attend with profit. The course will be taught by CAS/CNS faculty, as well as by distinguished guest lecturers at the beautiful and superbly equipped campus of the Wang Institute. An extraordinary range and depth of models, methods, and applications will be presented. Interaction with the lecturers and other participants will continue at the daily discussion sessions, meals, receptions, and coffee breaks that are included with registration. At the 1990 and 1991 courses, participants came from many countries and from all parts of the United States.

COURSE FACULTY FROM BOSTON UNIVERSITY

STEPHEN GROSSBERG, Wang Professor and Chairman of CNS, as well as professor of mathematics, psychology, and biomedical engineering, is one of the world's leading neural network pioneers and most versatile neural architects. The founder and first president of the International Neural Network Society (INNS), he is also founder and coeditor-in-chief of the INNS journal, *Neural Networks;* an editor of the journals *Neural Computation, Cognitive Science,* and *Brain Research;* founder and director of the Center for Adaptive Systems; general chairman of the 1987 IEEE First International Conference on Neural Networks (ICNN); and winner of the 1991 IEEE Neural Network Pioneer Award. Dr. Grossberg has introduced key models and computational methods of content addressable memory, associative learning, competitive learning, competitive and cooperative decision making, vision and image processing, speech and language processing, adaptive pattern recognition, cognitive information processing, reinforcement learning, and adaptive sensory-motor control. He is author of 200 articles and nine books about neural networks.

GAIL CARPENTER, professor of CNS and mathematics, is CNS director of graduate studies; 1989 vice president of INNS; organization chair of the 1988 INNS annual meeting; and an editor of the journals *Neural Networks, Neural Computation,* and *Brain Research.* Since receiving a PhD in mathematics (1974), she has carried out research on neural models of vision, nerve impulse generation (Hodgkin-Huxley equations), and complex biological rhythms. Dr. Carpenter is especially known for her work on developing the adaptive resonance theory architectures (ART 1, 2, and 3) for adaptive pattern recognition and category learning, for which she and Dr. Grossberg hold a series of patents. Her recent work incorporates ART modules into a family of neural systems for supervised learning of binary inputs (ARTMAP) or analog inputs (Fuzzy ARTMAP).

ENNIO MINGOLLA, assistant professor of CNS and psychology, is co-inventor with Dr. Grossberg of one of the first patented neural network architectures for vision and image processing (Boundary Contour System); co-organizer of the Third Workshop on Human and Machine Vision in 1985; editor of the journals *Neural Networks* and *Ecological Psychology;* a member of the DARPA neural network study panel on Adaptive Knowledge Processing; session chair for Vision and Image Processing at the 1987 IEEE ICNN and the 1988 annual INNS meeting; and invited speaker at the 1990 International Joint Conference on Neural Networks and the 1990 Neural Information Processing Symposium (NIPS).

DANIEL BULLOCK, associate professor of CNS and psychology, is a developer of neural network models for real-time adaptive sensory-motor control of arm movements and eye-arm coordination, notably the VITE and FLETE models for adaptive control of multi-joint trajectories; editor of *Neural Networks;* session chair for adaptive sensory-motor control and robotics at the 1987 ICNN and the 1988 annual INNS meeting; and invited speaker at the 1990 IJCNN and the 1990 International Symposium on Neural Networks for Sensory and Motor Systems. He is also known for his research in cognitive and developmental psychology.

COURSE GUEST LECTURERS

JOHN DAUGMAN received both his BA (1976) and PhD (1983) at Harvard University, where he subsequently joined the faculty and taught graduate and undergraduate courses in electrical engineering, computer science, and psychology. His areas of research are computational neuroscience, multidimensional signal processing and pattern recognition, and visual neurophysiology. He serves as an editor of *Brain Research* and *Neural Networks.* In 1988 he was awarded the Presidential Young Investigator Award by the U.S. National Science Foundation. During 1989–1990 he was the inaugural Professor of the Toshiba Endowed Chair in Computer Science at the Tokyo Institute of Technology, and in 1991 he was elected a member of the faculty of biology at Cambridge University.

FEDERICO FAGGIN, cofounder and president of Synaptics, Inc., received a doctoral degree in physics from the University of Padua, Italy, in 1965. In 1968 he joined the R & D laboratory of Fairchild Semiconductor in Palo Alto, California, where he developed the Silicon Gate Technology. In 1970, he joined the Intel Corporation, where he designed the first microprocessor. With Hal Feeney, he designed the first 8-bit microprocessor, and with M. Shima, the first high-performance 8-bit microprocessor. Dr. Faggin was cofounder, president, and CEO from its inception until the end of 1980 at Zilog, where he conceived the Z80 microprocessor family and directed design of the Z80-CPU. He started Cygnet Technologies in 1982 and became its president. Dr. Faggin has written many technical papers and holds many U.S. and foreign patents. He is the recipient of the 1988 Marconi Fellowship Award for his work on the microprocessor.

MICHAEL I. JORDAN, assistant professor of brain and cognitive sciences at the Massachusetts Institute of Technology, is a key developer of the recurrent back propagation algorithms. Professor Jordan's research is concerned with learning in recurrent networks and with the use of networks as forward models in planning and adaptive control. His interest in interdisciplinary research on neural networks is founded in his training for a bachelor's degree in psychology, a master's degree in mathematics, a doctoral degree in cognitive science, and postdoctoral research in computer science and has continued in his present position at MIT. Professor Jordan has given numerous invited lectures in the U.S., Italy, France, and Japan. He has taught in the Woods Hole summer school on Computational Neuroscience, the Connectionalist Models summer schools at Carnegie Mellon and UCSD, and was the co-organizer of the 1990 Cold Spring Harbor summer school on Computational Neuroscience.

ERIC SCHWARTZ is professor of neural sciences at NYU, associate professor of computer science at the Courant Institute, and associate professor of psychiatry at NYU Medical Center. His research interests include experimental studies of cortical visual architectures in monkeys and humans, and computational modeling of visual anatomy, physiology, and function. He introduced the term "Computational Neuroscience" in 1985 as the title of a symposium, which has recently appeared in book form. As a consultant with Vision Applications, Inc., he has designed and built a miniaturized video camera/actuator/computer system for performing real-time active vision, and is currently applying design principles of active vision toward a variety of commercial and defense applications.

ALEX WAIBEL is a senior research computer scientist in the computer science department of Carnegie Mellon University, with joint appointments in the Center for Machine Translation and the computational linguistics department. He is also a University Professor of Informatik at Karlsruhe University, Germany. He received a BS (1979) from the Massachusetts Institute of Technology, and an MS in electrical engineering and computer science (1980) and PhD in computer science (1986) from Carnegie Mellon University. Dr. Waibel has published many papers on speech recognition and synthesis, neurocomputing, machine learning, and machine translation. His 1989 paper on Time-Delay Neural Networks was awarded both the IEEE Signal Processing Society's senior paper award (1991) and the ATR best paper award (1990).

ALLEN WAXMAN received his BS in physics from the City College of New York (1973) and his PhD in astrophysics from the University of Chicago (1978). He has served on the faculties of MIT, Weizman Institute of Science, University of Maryland (Computer Vision Lab), and Boston University. Since 1989 he has been a member of the Senior Staff of MIT Lincoln Laboratory, Machine Intelligence Group. His work involves theoretical analysis and real-time computation of time-varying imagery, neural networks for spatio-temporal grouping and apparent motion, neural systems for 3-D object learning, and recognition by mobile robots.

Course 1 Schedule

SATURDAY, MAY 9, 1992

4:00–6:00 P.M. Registration

5:00–7:00 P.M. Reception

SUNDAY, MAY 10, 1992

8:00–10:00 A.M. MORNING SESSION (PROFESSOR GROSSBERG)

HISTORICAL OVERVIEW: Introduction to the binary, linear, and continuous-nonlinear streams of neural network research: McCulloch-Pitts, Rosenblatt, Von Neumann; Anderson, Kohonen, Widrow; Hodgkin-Huxley, Hartline-Ratliff, Grossberg.

COOPERATION AND COMPETITION: Analysis of asynchronous variable-load parallel processing by cooperative-competitive networks; solution of noise-saturation dilemma; classification of feedforward networks: automatic gain control, ratio processing, Weber law, total activity normalization, noise suppression, pattern matching, edge detection, brightness constancy and contrast; automatic compensation for variable illumination or other background energy distortions; classification of feedback networks: influence of nonlinear feedback signals, notably sigmoid signals, on pattern transformation and memory storage, winner-take-all choices, partial memory compression, tunable filtering, quantization and normalization of total activity, visual short-term memory, behavioral contrast, working memory for temporally ordered events.

CONTENT ADDRESSABLE MEMORY: Classification and analysis of neural network models for absolutely stable CAM. Models include: Cohen-Grossberg, additive, shunting, Brain-State-in-a-Box, Boltzmann Machine, McCulloch-Pitts, masking field, bidirectional associative memory.

10:00–10:30 A.M. Coffee Break

10:30 A.M.–12:30 P.M. MORNING SESSION (PROFESSOR GROSSBERG)

CONTENT ADDRESSABLE MEMORY, continued

ASSOCIATIVE LEARNING: Derivation of associative equations for short-term and long-term memory. Overview and analysis of associative outstars, instars, computational maps, avalanches, real-time learning of temporally ordered lists. Analysis of unbiased associative pattern learning by asynchronous parallel sampling channels. Classification of associative learning laws.

12:30–1:30 P.M. Lunch at Wang Institute

1:30–3:30 P.M. AFTERNOON SESSION (PROFESSORS CARPENTER, GROSSBERG, AND MINGOLLA)

ASSOCIATIVE LEARNING, continued

NEOCOGNITRON: Recognition and completion of images by a hierarchy of bottom-up adaptive filters and top-down attentive feedback.

PERCEPTRONS: Delta rule, gradient descent, adaptive statistical predictor, nonlinear separability, adaline, madaline.

INTRODUCTION TO BACK PROPAGATION: Supervised learning of multidimensional nonlinear maps by feedforward networks.

3:30–4:00 P.M. Coffee Break

4:00–6:00 P.M. AFTERNOON SESSION (PROFESSORS GROSSBERG AND MINGOLLA)

ADAPTIVE PATTERN RECOGNITION: Adaptive filtering; derivation and analysis of instar avalanches, competitive learning models, and 3-level universal associative maps; adaptive vector quantization; self-organizing feature maps; statistical properties of adaptive weights; learning stability and causes of instability; applications to cortical feature maps and traveling salesman problem.

6:00–7:15 P.M. Dinner at Wang Institute

7:15–8:30 P.M. EVENING SESSION DISCUSSIONS WITH LECTURERS AND INFORMAL PRESENTATIONS

MONDAY, MAY 11, 1992

8:00–10:00 A.M. MORNING SESSION (PROFESSORS CARPENTER AND GROSSBERG)

INTRODUCTION TO ADAPTIVE RESONANCE THEORY: Absolutely stable recognition learning; role of learned top-down expectations; attentional priming; matching by 2/3 Rule; adaptive search; self-controlled hypothesis testing; direct access to globally optimal recognition code; control of categorical coarseness by attentional vigilance; comparison with relevant behavioral and brain data to emphasize biological basis of ART computations.

ART 1: Analysis of ART 1 architecture for self-organized real-time hypothesis testing, learning, and recognition of arbitrary sequences of binary input patterns.

10:00–10:30 A.M. Coffee Break

10:30 A.M.–12:30 P.M. MORNING SESSION (PROFESSORS CARPENTER, GROSSBERG, AND MINGOLLA)

ART 2 AND ART 3: Analysis of ART 2 architecture for self-organized category learning and recognition of arbitrary sequences of analog or binary input patterns. ART 3 architecture for category learning in distributed network hierarchies; chemical transmitter and neuromodulator dynamics in forming a medium-term memory (MTM) representation distinct from short-term memory (STM) and long-term memory (LTM).

VISION AND IMAGE PROCESSING: Central problems in biological vision; differences between seeing and recognizing. Introduction to the Boundary Contour System (BCS) for emergent segmentation of edges, textures, and shading; illusory contours; processing of artificial sensor data; neurobiological correlates. Introduction to the Feature Contour System (FCS) for perceiving surface properties of brightness, color, and depth; discounting variable illumination and filling-in. Introduction to the Motion BCS; analysis of apparent motion; aperture problem, motion capture, rapid reset of coherent segmentations, different geometries for static orientations and motion directions.

12:30–1:30 P.M. Lunch at Wang Institute

1:30–3:30 P.M. AFTERNOON SESSION (PROFESSORS GROSSBERG AND MINGOLLA)

VISION AND IMAGE PROCESSING, continued

3:30–4:00 P.M. Coffee Break

4:00–6:00 P.M. AFTERNOON SESSION (PROFESSORS BULLOCK AND GROSSBERG)

ADAPTIVE SENSORY–MOTOR CONTROL AND ROBOTICS: Recent progress in adaptive sensory-motor control and related robotics research. Learning to foveate, reach, grasp, and transport objects of variable mass under visual guidance will be used as a target behavioral competence. Self-organization of reactive and planned eye movements; universal adaptive gain control by cerebellar learning; synchronous variable-speed control of multi-joint arm and speech articulator trajectories; analysis of behavioral and neural data about human and monkey arm movements; inverse kinematics; automatic compensation for unexpected perturbations; independent adaptive control of force and position by spinal circuits; adaptive control of position-dependent moment arms and motor plant nonlinearities by cerebellar learning; triphasic bursts during rapid movement and braking.

6:00–7:15 P.M. Dinner at Wang Institute

7:15–8:30 P.M. EVENING SESSION DISCUSSIONS WITH LECTURERS AND INFORMAL PRESENTATIONS

TUESDAY, MAY 12, 1992

S:00–10:00 A.M. MORNING SESSION
(PROFESSORS BULLOCK AND
GROSSBERG)

DAPTIVE SENSORY-MOTOR CONTROL
ND ROBOTICS, continued

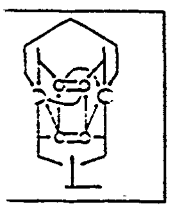
**EECH PERCEPTION AND PRODUC-
ON:** Introduction to speech perception
d production; circular reaction, imitation;
namics of working memory; multiple-
ale chunking by masking fields; categori-
perception; phonemic restoration;
ckward completion effects; resonant com-
tion and grouping of noisy variable-rate
ech streams.

10:00–10:30 A.M. Coffee Break

10:30 A.M.–12:30 P.M. MORNING SESSION
(PROFESSOR GROSSBERG)

**EINFORCEMENT LEARNING AND
EDICTION:** Reinforcement learning
rifies how external events interact with
ernal organismic needs and costs to trig-
learning processes that focus attention
d generate actions toward motivationally
sired goals. A neural network model of
nforcement learning will be derived.
nalysis of drive representations, adaptive
tics, conditioned reinforcers, role of moti-
tional feedback in focusing attention on
edictive data; attentional blocking and
blocking; adaptively timed responding;
ective forgetting; opponent processing;
nthesis of perception, recognition, rein-
cement, recall, and timing mechanisms
o a total neural architecture; neuro-
logical correlates.

d of Course 1



Course 2 Schedule

TUESDAY, MAY 12, 1992

11:30 A.M.–1:30 P.M. Registration

12:30 P.M.–1:30 P.M. Lunch at Wang Institute

1:30–3:30 P.M. AFTERNOON SESSION
(PROFESSOR CARPENTER)

ZZY ARTMAP: Incremental supervised
rning of recognition categories and multi-
nensional maps in response to arbitrary
uences of analog or binary input vectors;
ural network realizations of fuzzy logic;
ximal code compression and minimal
dictive error via match tracking; voting
ategies; benchmark comparisons with
k propagation, machine learning, and
netic algorithms.

3:30–4:00 P.M. Coffee Break

4:00–6:00 P.M. AFTERNOON SESSION
(DR. WAXMAN)

LEARNING 3-D OBJECTS FROM TEMPORAL SEQUENCES: Seibert-Waxman modular neural systems approach; feature extraction: shunting nets and the Diffusion-Enhancement Bilayer (DEB); invariances: adaptive eye motions via adalines; log-polar transform and grouping for scale and orientation invariance, overlapping receptive fields for deformation invariance; aspect categorization on the viewing sphere via ART 2; detecting and learning aspect transitions via the Aspect Net; evidence accumulation across a viewing sequence for recognition; implementation on a mobile robot with active vision.

6:00–7:15 P.M. Dinner at Wang Institute

7:15–8:30 P.M. EVENING SESSION
DISCUSSIONS WITH LECTURERS AND
INFORMAL PRESENTATIONS

WEDNESDAY, MAY 13, 1992

8:00–10:00 A.M. MORNING SESSION
(PROFESSOR JORDAN)

RECENT DEVELOPMENTS IN SUPERVISED LEARNING: Supervised learning in feedforward networks; the learning of inverse models; the problem of "teacher" in supervised learning; distal supervised learning and adaptive control; supervised learning in modular networks; supervised learning in hierarchical networks.

10:00–10:30 A.M. Coffee Break

10:30 A.M.–12:30 P.M. MORNING SESSION
(DR. WAIBEL)

SPEECH RECOGNITION AND UNDERSTANDING: Techniques in connectionist speech recognition and understanding. A brief introduction to the speech understanding problem; review of techniques for dynamic high-performance modeling of phonemes; methods for connectionist word and continuous speech recognition; neural network-based parsing and dialog modeling as applied to spoken language recognition and translation; state-of-the-art speech systems that employ connectionist techniques.

12:30–1:30 P.M. Lunch at Wang Institute

1:30–3:30 P.M. AFTERNOON SESSION
(PROFESSOR GROSSBERG)

VISION, SPACE, AND ACTION: Recent results on selected topics in 3-D vision, figure-ground separation, synchronous feature binding and motion perception; Vector Associative Map (VAM) models of fast autonomous error-based learning of multi-dimensional maps; automatic calibration of trajectory control parameters via rhythmic random sampling of the workspace; self-organization of head-centered and body-centered representations of 3-D space; spatial control of flexible motor trajectories.

3:30–4:00 P.M. Coffee Break

4:00–6:00 P.M. AFTERNOON SESSION
(PROFESSOR DAUGMAN)

SIGNAL PROCESSING IN NEURAL NETWORKS: Continuous-time and discrete-time signal processing in linear, nonlinear, and adaptive neural networks. Implementations of differential operators, convolution, feedback, transforms, matched filters, and learning in networks; issues of sampling, stability, orthogonality, noise, and scaling; extension to image processing, decision-under-uncertainty, and pattern recognition, with application demonstrated in a practical system of automatic face recognition.

6:00–7:15 P.M. Dinner at Wang Institute

7:15–8:30 P.M. EVENING SESSION
DISCUSSIONS WITH LECTURERS AND
INFORMAL PRESENTATIONS

THURSDAY, MAY 14, 1992

8:00–10:00 A.M. MORNING SESSION
(PROFESSOR SCHWARTZ)

ACTIVE VISION: Integration of robotic actuators into real-time machine vision systems. Biological background for space-variant (foveating) active vision; VLSI sensor architectures; robotic actuator design; control systems and control algorithms; visual attention algorithms; algorithms for pattern recognition with space-variant active vision systems; industrial applications; connections to computational neuroscience and brain dynamics.

10:00–10:30 A.M. Coffee Break

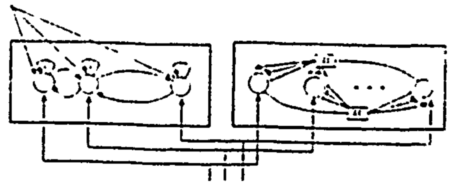
10:30 A.M.–12:30 P.M. MORNING SESSION
(DR. FAGGIN)

PRACTICAL IMPLEMENTATION OF NEURAL NETWORKS: Key issues relating to the practical implementation of neural networks; interdependence of neural network architecture and implementation technology; characteristics of various software and hardware implementations. An example of a commercially deployed application using a custom adaptive analog VLSI chip will be described in detail to further illustrate the trade-offs required when solving a real-world problem.

12:30–1:30 P.M. Lunch at Wang Institute

NEURAL NETWORKS FOR LEARNING, RECOGNITION, AND CONTROL

MAY 14-16, 1992



This international research conference on topics of fundamental importance in science and technology will bring together leading experts from universities, government, and industry to present their results on learning, recognition, and control, in invited lectures and contributed posters. Topics range from cognitive science and neurobiology through computational modeling to technological applications.

CALL FOR PAPERS: A featured poster session on neural network research related to learning, recognition, and control will be held on May 15, 1992. Attendees who wish to present a poster should submit three copies of an abstract (one single-spaced page), postmarked by March 1, 1992, for refereeing. Include a cover letter giving the name, address, and telephone number of the corresponding author. Mail to: Poster Session, Neural Networks Conference, Wang Institute of Boston University, 72 Tyng Road, Tyngsboro, MA 01879. Authors will be informed of abstract acceptance by March 31, 1992. A book of lecture and poster abstracts will be given to attendees at the conference.

CONFERENCE PROGRAM

THURSDAY, MAY 14, 1992

2:00–5:00 P.M. Registration

3:00–5:00 P.M. Reception

5:00–7:30 P.M. EVENING SESSION

5:00–5:50 P.M.
PROFESSOR RICHARD SHIFFRIN, INDIANA UNIVERSITY
"The Relationship between Composition / Distribution and Forgetting"

5:50–6:40 P.M.
PROFESSOR ROGER RATCLIFF, NORTHWESTERN UNIVERSITY
"Evaluating Memory Models"

6:40–7:30 P.M.
PROFESSOR DAVID RUMELHART, STANFORD UNIVERSITY
"Learning and Generalization in a Connectionist Network"

(Dinner not included with this evening's sessions)

FRIDAY, MAY 15, 1992

8:00 A.M.–12:40 P.M. MORNING SESSION

8:00–8:50 A.M.
DR. MORTIMER MISHKIN, NATIONAL INSTITUTE OF MENTAL HEALTH
"Two Cerebral Memory Systems"

8:50–9:40 A.M.
PROFESSOR LARRY SQUIRE, UNIVERSITY OF CALIFORNIA, SAN DIEGO
"Brain Systems and the Structure of Memory"

9:40–10:30 A.M.
PROFESSOR STEPHEN GROSSBERG, BOSTON UNIVERSITY
"Neural Dynamics of Adaptively Timed Learning and Memory"

10:30–11:00 A.M. Coffee Break

11:00–11:50 A.M.
PROFESSOR THEODORE BERGER, UNIVERSITY OF PITTSBURGH
"A Biological Neural Model for Learning and Memory"

11:50 A.M.–12:40 P.M.
PROFESSOR MARK BEAR, BROWN UNIVERSITY
"Mechanisms for Experience-Dependent Modification of Visual Cortex"

12:40–2:00 P.M. Lunch at Wang Institute

2:00–7:30 P.M. AFTERNOON SESSION

2:00–2:50 P.M.
PROFESSOR GAIL CARPENTER, BOSTON UNIVERSITY
"Supervised Learning by Adaptive Resonance Networks"

2:50–3:40 P.M.
DR. ALLEN WAXMAN, MIT LINCOLN LABORATORY
"Neural Networks for Mobile Robot Visual Navigation and Conditioning"

3:40–4:30 P.M.
DR. THOMAS CAUDELL, BOEING COMPANY
"The Industrial Application of Neural Networks to Information Retrieval and Object Recognition at the Boeing Company"

4:30–7:30 P.M. POSTER SESSION AND REFRESHMENTS

7:30–8:45 P.M. Dinner at Wang Institute

SATURDAY, MAY 16, 1992

8:00 A.M.–12:40 P.M. MORNING SESSION

8:00–8:50 A.M.
PROFESSOR GEORGE CYBENKO, UNIVERSITY OF ILLINOIS
"The Impact of Memory Technology on Neurocomputing"

8:50–9:40 A.M.
PROFESSOR EDUARDO SONTAG, RUTGERS UNIVERSITY
"Some Mathematical Results on Feedforward Nets: Recognition and Control"

9:40–10:30 A.M.
PROFESSOR ROGER BROCKETT, HARVARD UNIVERSITY
"A General Framework for Learning via Steepest Descent"

10:30–11:00 A.M. Coffee Break

11:00–11:50 A.M.
PROFESSOR BARRY PETERSON, NORTHWESTERN UNIVERSITY MEDICAL SCHOOL
"Approaches to Modeling a Plastic Vestibulo-ocular Reflex"

11:50 A.M.–12:40 P.M.
PROFESSOR DANIEL BULLOCK, BOSTON UNIVERSITY
"Spino-Cerebellar Cooperation for Skilled Movement Execution"

12:40–2:00 P.M. Lunch at Wang Institute

2:00–5:30 P.M. AFTERNOON SESSION

2:00–2:50 P.M.
DR. JAMES ALBUS, NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
"A System Architecture for Learning, Recognition, and Control"

2:50–3:40 P.M.
PROFESSOR KUMPATI NARENDRA, YALE UNIVERSITY
"Adaptive Control of Nonlinear Systems Using Neural Networks"

3:40–4:30 P.M.
DR. ROBERT PAP, ACCURATE AUTOMATION COMPANY
"Neural Network Control of the NASA Space Shuttle Robot Arm"

4:30–5:30 P.M. DISCUSSION

End of Research Conference

II. TRAINING OF PhD STUDENTS

The following 12 students were partially supported by the URI grant to do their PhD Thesis in our department. Their articles, thesis titles, and present jobs are also noted, where applicable.

Daniel Cruthirds (still at the CNS Department). Articles 34–35.

Gregory Francis, "Cortical models of visual perception", PhD degree, May 1993; now Assistant Professor of psychology at Purdue University. Articles 36–38.

Natalya Markuzon (still at the CNS Department). Articles 14–16.

Niall McLoughlin (still at the CNS Department).

David Pedini (still at the CNS Department).

John Reynolds, "Neural network architectures for learning, prediction, and probability estimation", PhD degree, May 1993; now a postdoctoral fellow at NIMH in the laboratory of Robert Desimone. Articles 14–22.

Karen Roberts (still at the CNS Department).

William Ross, "Neural network models of adaptive visual search and object recognition", PhD degree, May 1994. Articles 55–56.

Harald Ruda (still at the CNS Department).

Diglio Simoni (transferred to Syracuse University).

Vikas Taliwal (transferred to the Boston University Department of Mathematics).

Michael Tinnemeier, MA degree, May 1993.

In addition, the research support to the faculty enabled them to complete research articles with 10 more PhD students (Bradski, Gaudiano, Gove, Greve, Lesher, Pribe, Rosen, Somers, Williamson, Wyse). This research formed part of 8 completed PhD theses, and 2 more on the way.

III. COLLOQUIUM SERIES

An active colloquium series was partially supported by the URI grant. It presented an unusually broad interdisciplinary set of speakers, and was broadly advertised to and attended by scientists from around the greater Boston area. The lists of speakers over the three years of the grant are enclosed below.

Spring 1990 Colloquium Series

CENTER FOR ADAPTIVE SYSTEMS
GRADUATE PROGRAM IN COGNITIVE AND NEURAL SYSTEMS
BOSTON UNIVERSITY

February 6
ADAPTIVE RESONANCE THEORY: NEURAL NETWORK ARCHITECTURES FOR ADAPTIVE PATTERN RECOGNITION
Professor Gail Carpenter, Cognitive & Neural Systems Program *and* Department of Mathematics, Boston University

February 13
POSSIBLE MECHANISMS OF EXPERIENCE-DEPENDENT SYNAPTIC PLASTICITY IN VISUAL CORTEX
Professor Mark Bear, Center for Neural Science, Brown University

February 27
CONTROLLING CONTACT IN ROBOTIC AND BIOLOGICAL SYSTEMS
Professor Neville Hogan, Department of Mechanical Engineering, M.I.T.

March 20
MEMORY REPRESENTATION IN THE HIPPOCAMPUS
Professor Howard Eichenbaum, Department of Biological Sciences, Wellesley College

March 27
MULTIPLE VISUAL ANALYSES: THE MANY DOORS OF PERCEPTION
Professor Patrick Cavanaugh, Department of Psychology, Harvard University

April 3
MINL MAPPING
Professor Michael Gazzaniga, Program in Cognitive Neuroscience, Dartmouth Medical School

April 10
CEREBRAL CORTICAL NEURONAL REPRESENTATIONS OF MOVEMENT, DYNAMICS, AND KINEMATICS
Professor John Kalaska, Centre de Recherche en Sciences Neurologiques, Université de Montreal

April 17
SPEECH PERCEPTION: STRUCTURE OF PHONETIC CATEGORIES
Professor Joanne Miller, Department of Psychology, Northeastern University

All Talks on Tuesdays at 3:30 PM in Room 149
Refreshments at 3:00 PM in Room 241
111 Cummington Street, Boston

—PLEASE POST—

Fall 1990 Colloquium Series

CENTER FOR ADAPTIVE SYSTEMS
AND
GRADUATE PROGRAM IN COGNITIVE AND NEURAL SYSTEMS
BOSTON UNIVERSITY

September 18
ADAPTIVE NEURAL DYNAMICS OF PLANNED AND REACTIVE ARM MOVEMENTS
Professor Stephen Grossberg. Wang Professor of Cognitive and Neural Systems. Boston University: and **Professor Daniel Bullock**. Associate Professor of Cognitive and Neural Systems and Psychology. Boston University.
(This two part talk will run from 3:30–5 p.m.)

September 25
BIOCHEMICAL MODEL FOR THE HEBB AND ANTI-HEBB PROCESSES UNDERLYING SYNAPTIC PLASTICITY AND MEMORY
Professor John Lisman. Professor of Biology. Brandeis University.

October 2
ROBUST SPEECH RECOGNITION USING HIDDEN MARKOV MODELS
Dr. Doug Paul. Speech Systems Technology Group. MIT Lincoln Labs.

October 9
AMACRONIC SENSOR TECHNOLOGY
Dr. Wilfrid Veldkamp. Group Leader. Binary Optics Group. MIT Lincoln Labs.

October 16
PRINCIPLES OF ANATOMIC ORGANIZATION OF THE PRIMATE CEREBRAL CORTEX: IMPLICATIONS FOR CORTICAL EVOLUTION
Professor Helen Barbas. Associate Professor of Health Sciences. Anatomy. and Neurobiology. Boston University.

October 23
NEURONAL CORRELATES OF MOTION PERCEPTION
Dr. Nikos Logothetis. Department of Brain and Cognitive Sciences. MIT.

November 13
MODULAR ORGANIZATION OF NEURONS IN CEREBRAL CORTEX
Professor Alan Peters. Chairman and Waterhouse Professor of Anatomy and Neurobiology. Boston University Medical School.

November 20
L'ART POUR L'ART: MODELING MUSICAL PERCEPTION
Professor Robert Gjerdingen. Associate Professor of Music Theory. State University of New York at Stony Brook.

December 4
THE PERCEPTION OF MOTION
Professor James Todd. Professor of Psychology and Center for Complex Systems. Brandeis University.

All Talks on Tuesdays at 3:30 PM in Room 149
Refreshments at 3:00 PM in Room 241
111 Cummington Street. Boston

— PLEASE POST —

Spring 1991 Colloquium Series

CENTER FOR ADAPTIVE SYSTEMS
AND
GRADUATE PROGRAM IN COGNITIVE AND NEURAL SYSTEMS
BOSTON UNIVERSITY

January 22
KNOWLEDGE REPRESENTATION AND COMPUTING ON THE BASIS OF SIMILARITY AND ASSOCIATIVITY
Professor Yoh-Han Pao, Departments of Electrical Engineering and Computer Science, Case Western Reserve University

January 29
EFFORTFUL TOUCH
Professor Michael Turvey. Professor of Psychology. University of Connecticut

February 5
HEBBIAN COMPUTATIONS IN HIPPOCAMPAL NEURONS
Professor Thomas H. Brown, Department of Psychology, Yale University

February 12
NEURAL NETWORK CONTROLLER FOR ADAPTIVE SENSORY-MOTOR COORDINATION: DESIGNING AN 'INFANT' TO BEHAVE
Dr. Michael Kuperstein, President, Neurogen Corporation

February 19
EYE MOVEMENTS IN THE NATURAL WORLD
Professor Eileen Kowler, Psychology Department. Rutgers University

March 12
HERMITE POLYNOMIALS AS BASIS FUNCTIONS FOR VISION
Professor Adam Reeves. Psychology Department. Northeastern University

March 19
NEURAL DYNAMICS OF VISUAL MOTION SEGMENTATION
Professor Ennio Mingolla, Cognitive and Neural Systems Graduate Program and Psychology Department, Boston University

April 2
ROLE OF PROPRIOCEPTIVE INFORMATION IN THE PLANNING AND CONTROL OF MULTI-JOINT MOVEMENT
Professor Claude Ghez, Center for Neurobiology and Behavior, Columbia University

April 9
DYNAMIC LEGGED ROBOTS
Professor Mark Raibert, Artificial Intelligence Laboratory, MIT

April 16
ORIENTATION SELECTIVITY PREFERENCE AND CONTINUITY IN MONKEY STRIATE CORTEX
Professor Gary Blasdel, Department of Neurobiology, Harvard University

All Talks on Tuesdays at 3:30 PM in Room 149
Refreshments at 3:00 PM in Room 241
111 Cummington Street, Boston

••• PLEASE POST •••

••• REVISED ANNOUNCEMENT •••

Spring 1991 Colloquium Series

CENTER FOR ADAPTIVE SYSTEMS
AND
GRADUATE PROGRAM IN COGNITIVE AND NEURAL SYSTEMS
BOSTON UNIVERSITY

- February 19 (Newly scheduled)
  NEURONAL DYNAMICS IN PRIMATE VISION
  Dr. Timothy Gawne, Laboratory of Neuropsychology, National Institute of Mental Health

March 12
HERMITE POLYNOMIALS AS BASIS FUNCTIONS FOR VISION
Professor Adam Reeves, Psychology Department, Northeastern University

- March 19 (Formerly scheduled for February 19)
  EYE MOVEMENTS IN THE NATURAL WORLD
  Professor Eileen Kowler, Psychology Department, Rutgers University

- March 26 (Formerly scheduled for March 19)
  NEURAL DYNAMICS OF VISUAL MOTION SEGMENTATION
  Professor Ennio Mingolla, Cognitive and Neural Systems Graduate Program and Psychology Department, Boston University

April 2
ROLE OF PROPRIOCEPTIVE INFORMATION IN THE PLANNING AND CONTROL OF MULTI-JOINT MOVEMENT
Professor Claude Ghez, Center for Neurobiology and Behavior, Columbia University

April 9
DYNAMIC LEGGED ROBOTS
Professor Mark Raibert, Artificial Intelligence Laboratory, MIT

April 16
ORIENTATION SELECTIVITY PREFERENCE AND CONTINUITY IN MONKEY STRIATE CORTEX
Professor Gary Blasdel, Department of Neurobiology, Harvard University

All Talks on Tuesdays at 3:30 PM in Room 149
Refreshments at 3:00 PM in Room 241
111 Cummington Street, Boston

••• PLEASE POST •••

CENTER FOR ADAPTIVE SYSTEMS
AND
DEPARTMENT OF COGNITIVE AND NEURAL SYSTEMS
BOSTON UNIVERSITY

September 17
TESTING MULTI-INPUT NONLINEAR NETWORK MODELS FOR MONKEY STRIATE NEURONS
Professor Lowell Jacobson, Department of Neurology, University of Massachusetts Medical Center

September 24
GENERALIZATION, REGULARIZATION, AND ARCHITECTURE SELECTION IN NONLINEAR LEARNING SYSTEMS
Professor John Moody, Department of Computer Science, Yale University

October 1
COGNITIVE NOVELTY VERSUS COGNITIVE ROUTINIZATION IN CEREBRAL HEMISPHERES
Professor Elkhonon Goldberg, Division of Neuropsychology, Medical College of Pennsylvania

October 8
DESIGN OF RETINAL CIRCUITS FOR EFFICIENT CODING OF THE NATURAL SCENE
Professor Peter Sterling, Department of Anatomy, University of Pennsylvania

October 22
SOME MATHEMATICAL ISSUES CONCERNING FEEDFORWARD NETS
Professor Eduardo Sontag, Department of Mathematics, Rutgers University

November 12
MATHEMATICAL MODELS FOR ANALOG COMPUTATION
Professor Roger Brockett, Division of Applied Sciences, Harvard University

December 3
SUPERVISED LEARNING BY ADAPTIVE RESONANCE NETWORKS
Professor Gail A. Carpenter, Department of Cognitive and Neural Systems, Boston University

December 10
AUDITORY SCENE ANALYSIS
Professor Albert Bregman, Department of Psychology, McGill University

All Talks on Tuesdays at 3:30 PM in Room 149
Refreshments at 3:00 PM in Room 241
111 Cummington Street, Boston

••• PLEASE POST •••

••• Spring 1992 Colloquium Series •••

CENTER FOR ADAPTIVE SYSTEMS
AND
DEPARTMENT OF COGNITIVE AND NEURAL SYSTEMS
BOSTON UNIVERSITY

January 28
CONSTRUCTING CAMS: THE SYNTHESIS OF ARBITRARY STABLE DYNAMICS
Professor Michael Cohen. Department of Cognitive and Neural Systems and Computer Science Department. Boston University

February 4
EPIGENETICS OF NEURAL NETWORKS AND IMPLICATIONS FOR LANGUAGE
Professor Elie Bienenstock. Division of Applied Mathematics. Brown University

February 11
TOWARDS A UNIFIED MODEL OF SPATIO-TEMPORAL VISUAL PROCESSING: SIMULATION OF RESULTS FROM RETINAL PHYSIOLOGY
Professor Paolo Gaudiano. Department of Cognitive and Neural Systems. Boston University

February 25
IS THERE ATTENTIONAL SELECTION OF ITEMS BY FEATURE AS WELL AS BY LOCATION?
Professor George Sperling. Psychology Department and Center for Neural Sciences. New York University

March 5 (a Thursday!)
CONNECTIONISM AND THE CORE ISSUES IN LANGUAGE DEVELOPMENT
Professor Brian MacWhinney. Psychology Department. Carnegie-Mellon University

March 17
COARSE CODING AND THE LEXICON
Professor Catherine Harris. Psychology Department. Boston University

March 31
POSTURAL FORCE FIELDS IN THE HUMAN ARM AND THEIR ROLE IN INITIATION OF MOVEMENT
Reza Shadmehr, McDonnell-Pew Fellow. Brain and Cognitive Sciences Department. Massachusetts Institute of Technology

April 14
HANDWRITING GENERATION AND HUMAN MOVEMENT MODELING
Professor Réjean Plamondon, Department of Electrical Engineering and Computer Science. University of Montreal

April 21
HOW CAN PHYSIOLOGISTS TEST NEURAL NETWORK MODELS? INSIGHTS FROM STUDIES OF QUADRATURE PHASE AND ANTIPHASE PAIR FORMATION IN THE STRIATE CORTEX
Professor Dan Pollen. Department of Neurology. University of Massachusetts Medical School and **Zheng Liu.** Department of Applied Sciences. Harvard University.

All Talks (but March 5) are on Tuesdays at 3:30 PM in Room 149
Refreshments at 3:00 PM in Room 241
111 Cummington Street. Boston

••• PLEASE POST •••

Fall 1992 Colloquium Series

CENTER FOR ADAPTIVE SYSTEMS AND DEPARTMENT OF COGNITIVE AND NEURAL SYSTEMS BOSTON UNIVERSITY

September 22
EXPRESSIVE TIMING IN MUSIC PERFORMANCE
Dr. Bruno Repp, Haskins Laboratories

September 29
A NEURAL NETWORK MODEL OF ADAPTIVELY TIMED REINFORCEMENT LEARNING AND HIPPOCAMPAL DYNAMICS
Professor Stephen Grossberg, Department of Cognitive and Neural Systems, Boston University

October 6
IS THERE MOTOR PROGRAM GENERALIZATION: EXAMINING THE QUESTION AND ITS ANSWER
Professor Charles Wright, Department of Psychology, Columbia University

October 13
IMPLICIT MEMORY IN AMNESIA
Dr. Laird Cermak, Memory Disorders Research Center, Boston VA Hospital

October 20
VISUAL PATTERN RECOGNITION AND THE TEMPORAL LOBES
Professor Charles Gross, Department of Psychology, Princeton University

November 3 **TALK CANCELLED**

November 10
MAGNETIC RESONANCE IMAGING OF THE HUMAN BRAIN: FROM STRUCTURE TO FUNCTION
Professor David Kennedy, Professor of Neurology, Harvard Medical School, and Center for Morphometric Analysis, Massachusetts General Hospital

November 17
TOPOLOGY AND TOPOGRAPHY IN PRIMATE VISUAL CORTEX: TOWARDS A UNIFIED COMPUTATIONAL MODEL OF FUNCTIONAL ARCHITECTURE
Professor Eric Schwartz, Department of Cognitive and Neural Systems, Boston University

November 24
THEORETICAL RESULTS IN MEMORY-BASED LEARNING
Professor George Cybenko, Thayer School of Engineering, Dartmouth College

December 1
GEOMETRY AND BIOPHYSICS: SOME CASE STUDIES
Professor Nancy Kopell, Department of Mathematics, Boston University

December 8
IMPLICIT MEMORY IN THE AUDITORY DOMAIN: COGNITIVE AND NEUROPSYCHOLOGICAL ANALYSES
Professor Daniel Schacter, Department of Psychology, Harvard University

All Talks on Tuesdays at 3:30 PM in Room 149
Refreshments at 3:00 PM in Room 241
111 Cummington Street, Boston

PLEASE POST

••• Spring 1993 Colloquium Series •••

CENTER FOR ADAPTIVE SYSTEMS
AND
DEPARTMENT OF COGNITIVE AND NEURAL SYSTEMS
BOSTON UNIVERSITY

February 9
THE NEUROBEHAVIORAL BASES FOR THE REWARDING EFFECTS OF ABUSED DRUGS
Professor Conan Kornetsky, Department of Psychiatry, Boston University Medical School

March 2
POSTURE BASED PLANNING FOR MOVEMENT
Professor David Rosenbaum, Department of Psychology, University of Massachusetts at Amherst

March 16
SENSORY MOTOR ADAPTATION TO UNUSUAL FORCE ENVIRONMENTS
Professor James Lackner, Ashton Graybiel Spatial Orientation Lab, Brandeis University

March 23
THE BASAL GANGLIA AND MOTOR CONTROL
Professor Ann Graybiel, Department of Brain and Cognitive Sciences, MIT

March 30
COMPUTATION OF MOTION SIGNALS IN THE VISUAL CORTEX (OF CAT) AND ITS RELATION TO MOTION ENERGY
Professor Robert Emerson, Center for Visual Science, University of Rochester

April 13
DYNAMIC PROPERTIES OF ADULT VISUAL CORTEX
Professor Charles Gilbert, Department of Neurobiology, Rockefeller University

April 20
MOTION PERCEPTION: HOW THE BRAIN DEALS WITH 1000 POINTS OF LIGHT
Professor Robert Sekuler, Department of Biomedical Engineering, Boston University *and* Department of Psychology, Brandeis University

All Talks are on Tuesdays at 3:30 PM in Room 149
Refreshments at 3:00 PM in Room 241
111 Cummington Street, Boston

••• PLEASE POST •••

IV. BOSTON UNIVERSITY PUBLICATIONS PARTIALLY SUPPORTED BY THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Contract AFOSR 90-0175
January 1, 1990–April 15, 1993

BOOKS

1. Carpenter, G.A. and Grossberg, S. (Eds.) (1991). **Pattern recognition by self-organizing neural networks.** Cambridge, MA: MIT Press. (*%#+)
2. Carpenter, G.A. and Grossberg, S. (Eds.) (1992). **Neural networks for vision and image processing.** Cambridge, MA: MIT Press. (*%#+@)
3. Commons, M., Grossberg, S., and Staddon, J.E.R. (Eds.). (1991). **Neural network models of conditioning and action.** Hillsdale, NJ: Erlbaum Associates.
4. Grossberg, S. (1992). **Neural networks and natural intelligence.** Cambridge, MA: MIT Press (paperback edition).

ARTICLES

1. Bradski, G., Carpenter, G.A., and Grossberg, S. (1991). Working memory networks for learning multiple groupings of temporally ordered events: Applications to 3-D visual object recognition. In **Proceedings of the international joint conference on neural networks**, Seattle, **I**, 723–728. Piscataway, NJ: IEEE Service Center. (%#+)
2. Bradski, G., Carpenter, G.A., and Grossberg, S. (1992). Working memory networks for learning temporal order with application to three-dimensional visual object recognition. *Neural Computation*, **4**, 270–286. (%#+@)
3. Bradski, G., Carpenter, G.A., and Grossberg, S. (1992). Working memories for storage and recall of arbitrary temporal sequences. In **Proceedings of the international joint conference on neural networks**, Baltimore, **II**, 57–62. Piscataway, NJ: IEEE Service Center. (%#+@)
4. Bradski, G., Carpenter, G.A., and Grossberg, S. (1992). STORE working memory networks for storage and recall of arbitrary temporal sequences. **Technical Report CAS/CNS-TR-92-028**, Boston University. Submitted for publication. (%#+@)
5. Bullock, D. and Grossberg, S. (1991). Adaptive neural networks for control of movement trajectories invariant under speed and force rescaling. *Human Movement Science*, **10**, 3–53. (+)
6. Bullock, D. and Grossberg, S. (1991). Reply to Commentators for the Target Article "Adaptive neural networks for control of movement trajectories invariant under speed and force rescaling." *Human Movement Science*, **10**, 133–157. (+)
7. Bullock, D. and Grossberg, S. (1992). Emergence of tri-phasic muscle activation from the nonlinear interactions of central and spinal neural network circuits. *Human Movement Science*, **11**, 157–167. (# +)
8. Carpenter, G.A. and Grossberg, S. (1991). Distributed hypothesis testing, attention shifts, and transmitter dynamics during the self-organization of brain recognition codes.

In H.G. Schuster and W. Singer (Eds.), **Nonlinear dynamics and neuronal networks.** New York: Springer-Verlag, pp. 305–334. (*%#+)

9. Carpenter, G.A. and Grossberg, S. (1992). Adaptive resonance theory. **Encyclopedia of artificial intelligence, Second edition.** New York: Wiley and Sons, pp. 13–21. (%*#+)
10. Carpenter, G.A. and Grossberg, S. (1992). Self-organizing cortical networks for distributed hypothesis testing and recognition learning. In J.G. Taylor and C.L.T. Mannion (Eds.), **Theory and applications of neural networks.** London: Springer-Verlag, pp. 3–27. (*%#+)
11. Carpenter, G.A. and Grossberg, S. (1993). Normal and amnesic learning, recognition, and memory by a neural model of cortico-hippocampal interactions. *Trends in Neurosciences*, **16**, 131–137. (%#+@)
12. Carpenter, G.A., Grossberg, S., and Iizuka, K. (1992). Comparative performance measures of Fuzzy ARTMAP, learned vector quantization, and back propagation for handwritten character recognition. In **Proceedings of the international joint conference on neural networks**, Baltimore, **I**, 794–799. Piscataway, NJ: IEEE Service Center. (%#+@)
13. Carpenter, G.A., Grossberg, S., and Lesher, G.W. (1992). A what-and-where neural network for invariant image preprocessing. In **Proceedings of the international joint conference on neural networks**, Baltimore, **III**, 303–308. Piscataway, NJ: IEEE Service Center. (%#+@)
14. Carpenter, G.A., Grossberg, S., Markuzon, N., Reynolds, J.H., and Rosen, D.B. (1992). Fuzzy ARTMAP: An adaptive resonance architecture for incremental learning of analog maps. In **Proceedings of the international joint conference on neural networks**, Baltimore, **III**, 309–314. Piscataway, NJ: IEEE Service Center. (%#+@)
15. Carpenter, G.A., Grossberg, S., Markuzon, N., Reynolds, J.H., and Rosen, D.B. (1992). Fuzzy ARTMAP: A neural network architecture for incremental supervised learning of amnalog multidimensional maps. *IEEE Transactions on Neural Networks*, **3**, 698–713. (%#+@)
16. Carpenter, G.A., Grossberg, S., Markuzon, N., Reynolds, J.H., and Rosen, D.B. (1992). Supervised learning by adaptive resonance neural networks. In M. Marinaro and G. Scarpetta (Eds.), **Structure: From physics to general systems.** Singapore: World Scientific Publishing Company, **2**, 36–63. (%#+@)
17. Carpenter, G.A., Grossberg, S., and Reynolds, J.H. (1991). ARTMAP: Supervised real-time learning and classification of nonstationary data by a self-organizing neural network. *Neural Networks*, **4**, 565–588. (*%#+)
18. Carpenter, G.A., Grossberg, S., and Reynolds, J.H. (1991). A self-organizing ARTMAP neural architecture for supervised learning and pattern recognition. In R. Mammone and Y. Zeevi (Eds.), **Neural networks: Theory and applications.** New York: Academic Press. (*%#+)
19. Carpenter, G.A., Grossberg, S., and Reynolds, J.H. (1991). ARTMAP: A self-organizing neural network architecture for fast supervised learning and pattern recognition. In T. Kohonen, K. Mäkisara, O. Simula, and J. Kangas (Eds.), **Artificial neural networks,**

Volume 1. Amsterdam: Elsevier, pp. 31–36. (*%#+)

20. Carpenter, G.A., Grossberg, S., and Reynolds, J.H. (1991). ARTMAP: A self-organizing neural network architecture for fast supervised learning and pattern recognition. In **Proceedings of the international joint conference on neural networks**, Seattle, **I**, 863–868. Piscataway, NJ: IEEE Service Center. (*%#+)
21. Carpenter, G.A., Grossberg, S., and Reynolds, J.H. (1992). A neural network architecture for fast on-line supervised learning and pattern recognition. In H. Wechsler (Ed.), **Neural networks for human and machine perception**. New York: Academic Press, pp. 248–264. (*%#+)
22. Carpenter, G.A., Grossberg, S., and Reynolds, J.H. (1993). Fuzzy ARTMAP, slow learning, and probability estimation. **Technical Report CAS/CNS-TR-93-014**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **II**, 26–30. Hillsdale, NJ: Erlbaum Associates. (%#+@)
23. Carpenter, G.A., Grossberg, S., and Rosen, D.B. (1991). ART2-A: An adaptive resonance algorithm for rapid category learning and recognition. *Neural Networks*, **4**, 493–504. (*%#+)
24. Carpenter, G.A., Grossberg, S., and Rosen, D.B. (1991). ART2-A: An adaptive resonance algorithm for rapid category learning and recognition. In **Proceedings of the international joint conference on neural networks**, Seattle, **II**, 151–156. Piscataway, NJ: IEEE Service Center. (*%#+)
25. Carpenter, G.A., Grossberg, S., and Rosen, D.B. (1991). Fuzzy ART: Fast stable learning and categorization of analog patterns by an adaptive resonance system. *Neural Networks*, **4**, 759–771. (*%#+)
26. Carpenter, G.A., Grossberg, S., and Rosen, D.B. (1991). Fuzzy ART: Fast stable learning and categorization of analog patterns by an adaptive resonance system. In **Proceedings of the international joint conference on neural networks**, Seattle, **II**, 411–420. (*%#+)
27. Cohen, M.A., Grossberg, S., and Pribe, C. (1992). A neural pattern generator that exhibits frequency-dependent in-phase and anti-phase oscillations. In **Proceedings of the international joint conference on neural networks, IV**, 146–151. Piscataway, NJ: IEEE Service Center. (%#+@)
28. Cohen, M.A., Grossberg, S., and Pribe, C. (1992). A neural pattern generator that exhibits frequency-dependent in-phase and anti-phase oscillations and quadruped gait transitions. **Technical Report CAS/CNS-TR-92-008**, Boston University. Submitted for publication. (*+)
29. Cohen, M.A., Grossberg, S., and Pribe, C. (1993). Neural control of interlimb coordination and gait timing in bipeds and quadrupeds. **Technical Report CAS/CNS-TR-93-004**, Boston University. Submitted for publication. (*#+@)
30. Cohen, M.A., Grossberg, S., and Pribe, C. (1993). A neural pattern generator that exhibits arousal-dependent human gait transitions. **Technical Report CAS/CNS-TR-93-017**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **IV**, 285–288. Hillsdale, NJ: Erlbaum Associates. (#+@)
31. Cohen, M.A., Grossberg, S., and Pribe, C. (1993). Frequency-dependent phase transi-

tions in the coordination of human bimanual tasks. **Technical Report CAS/CNS-TR-93-018**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **IV**, 491–494. Hillsdale, NJ: Erlbaum Associates. (#+@)

32. Cohen, M.A., Grossberg, S., and Pribe, C. (1993). Quadruped gait transitions from a neural pattern generator with arousal modulated interactions. **Technical Report CAS/CNS-TR-93-019**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **II**, 610–613. Hillsdale, NJ: Erlbaum Associates. (#+@)

33. Cohen, M.A., Grossberg, S., and Wyse, L. (1992). A neural network for synthesizing the pitch of an acoustic source. **Technical Report CAS/CNS-TR-92-009**, Boston University. In **Proceedings of the international joint conference on neural networks**, **IV**, 649–654. Piscataway, NJ: IEEE Service Center. (%#+@)

34. Cruthirds, D., Gove, A., Grossberg, S., and Mingolla, E. (1991). Preattentive texture segmentation and grouping by the boundary contour system. In **Proceedings of the international joint conference on neural networks**, Seattle, **I**, 655–660. Piscataway, NJ: IEEE Service Center. (#=)

35. Cruthirds, D., Gove, A., Grossberg, S., Mingolla, E., Nowak, N., and Williamson, J. (1992). Processing of synthetic aperture radar images by the Boundary Contour System. In **Proceedings of the international joint conference on neural networks**, Baltimore, **IV**, 414–417. Piscataway, NJ: IEEE Service Center. (%#+@)

36. Francis, G., Grossberg, S., and Mingolla, E. (1994). Cortical dynamics of feature binding and reset: Control of visual persistence. *Vision Research*, in press. (#+)

37. Francis, G., Grossberg, S., and Mingolla, E. (1993). Dynamic reset of persistent visual segmentations by neural networks. In **Proceedings of the world congress on neural networks**, Portland, **II**, 108–111. Hillsdale, NJ: Erlbaum Associates. (#+@)

38. Francis, G., Grossberg, S., and Mingolla, E. (1993). Dynamic formation and reset of coherent visual segmentations by neural networks. In R. Mammone (Ed.), **Artificial neural networks for speech and vision**. London: Chapman and Hall, pp. 474–501. (#@)

39. Gaudiano, P. and Grossberg, S. (1991). Vector associative maps: Unsupervised real-time error-based learning and control of movement trajectories. *Neural Networks*, **4**, 147–183. (#+)

40. Gaudiano, P. and Grossberg, S. (1991). Self-organization of spatial representations and arm trajectory controllers by vector associative maps energized by cyclic random generators. In A. Babloyantz (Ed.), **Self-organization, emerging properties and learning.** London: Plenum Press. (#+)

41. Gaudiano, P. and Grossberg, S. (1992). Adaptive vector integration to endpoint: Self-organizing neural circuits for control of planned movement trajectories. *Human Movement Science*, **11**, 141–155. (#+)

42. Gove, A., Grossberg, S., and Mingolla, E. (1993). Brightness perception, illusory contours, and corticogeniculate feedback. **Technical Report CAS/CNS-TR-93-021**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **I**, 25–28. Hillsdale, NJ: Erlbaum Associates. (#@)

43. Greve, D., Grossberg, S., Guenther, F., and Bullock, D. (1993). Neural representa-

tions for sensory-motor control, I: Head-centered 3-D target positions from opponent eye commands. *Acta Psychologica*, **82**, 115–138. (#+)

44. Grossberg, S. (1991). Why do parallel cortical systems exist for the perception of static form and moving form? *Perception and Psychophysics*, **49**, 117–141. (*#=)
45. Grossberg, S. (1992). The symmetric organization of parallel cortical systems for form and motion perception. In H. Wechsler (Ed.), **Neural networks for human and machine perception.** New York: Academic Press, pp. 64–103. (#=)
46. Grossberg, S. (1992). Why do parallel cortical systems exist for the perception of static form and moving form? In G.A. Carpenter and S. Grossberg (Eds.), **Neural networks for vision and image processing.** Cambridge, MA: MIT Press, pp. 247–292. (*#=)
47. Grossberg, S. (1993). A solution of the figure-ground problem for biological vision. *Neural Networks*, **6**, 463–483. (#@)
48. Grossberg, S. (1994). 3-D vision and figure-ground separation by visual cortex. **Technical Report CAS/CNS-TR-92-019**, Boston University. *Perception and Psychophysics*, **55**, 48–120. (#)
49. Grossberg, S. (1994). Cortical dynamics of 3-D vision and figure-ground pop-out. **Technical Report CAS/CNS-TR-92-023**, Boston University. In **Proceedings of the Danish Royal Academy of Sciences and Letters.** Copenhagen, Denmark: in press. (#@)
50. Grossberg, S. and Mingolla, E. (1990). Neural dynamics of motion segmentation. Invited article in **Proceedings of graphics interface/vision interface 90**, Halifax, Nova Scotia, May 17, 1990. Toronto: Canadian Information Processing Society, pp. 112–119. (*)
51. Grossberg, S. and Mingolla, E. (1990). Neural dynamics of motion segmentation: Direction fields, apertures, and resonant grouping. In M. Caudill (Ed.), **Proceedings of the international joint conference on neural networks**, January, **I**, 11–14. Hillsdale, NJ: Erlbaum Associates. (*#)
52. Grossberg, S. and Mingolla, E. (1992). Neural dynamics of visual motion perception: Local detection and global grouping. In G.A. Carpenter and S. Grossberg (Eds.), **Neural networks for vision and image processing.** Cambridge, MA: MIT Press, pp. 293-342. (*#)
53. Grossberg, S. and Mingolla, E. (1993). Neural dynamics of motion segmentation: Direction fields, apertures, and resonant grouping. *Perception and Psychophysics*, **53**, 243–278. (*#)
54. Grossberg, S. and Mingolla, E. (1994). Visual motion perception. In V.S. Ramachandran (Ed.), **Encyclopedia of human behavior.** New York: Academic Press, in press. (#@)
55. Grossberg, S., Mingolla, E., and Ross, W.D. (1993). A neural theory of visual search: Recursive attention to segmentations and surfaces. **Technical Report CAS/CNS-TR-93-023**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **I**, 36–41. Hillsdale, NJ: Erlbaum Associates. (#+@)
56. Grossberg, S., Mingolla, E., and Ross, W.D. (1994). A neural theory of attentive visual search: Interactions of visual, spatial, and object representations. **Technical Report CAS/CNS-TR-93-038**, Boston University. *Psychological Review*, in press. (#+@)

57. Grossberg, S., Mingolla, E., and Williamson, J. (1993). Processing of synthetic aperture radar images by a multiscale Boundary Contour System and Feature Contour System. **Technical Report CAS/CNS-TR-93-024**, Boston University. In **Proceedings of the world congress on neural networks, III**, 785–788. Hillsdale, NJ: Erlbaum Associates. (#@)

58. Grossberg, S. and Rudd, M.E. (1991). A neural theory of visual motion perception. In B. Blum (Ed.), **Channels in the visual nervous system: Neurophysiology, psychophysics, and models**. Tel Aviv: Freund Publishing Ltd. (*#)

59. Grossberg, S. and Rudd, M.E. (1992). Cortical dynamics of visual motion perception: Short-range and long-range apparent motion. *Psychological Review*, **99**, 78–121. (*#=)

60. Grossberg, S. and Somers, D. (1991). Synchronized oscillations during cooperative feature linking in a cortical model of visual perception. *Neural Networks*, **4**, 453–466. (*#&)

61. Grossberg, S. and Somers, D. (1991). Synchronized oscillations during cooperative feature linking in a cortical model of visual perception. In **Proceedings of the international joint conference on neural networks**, Seattle, **II**, 249–254. Piscataway, NJ: IEEE Service Center. (*#&)

62. Grossberg, S. and Somers, D. (1991). Synchronized oscillations during cooperative feature linking in visual cortex. In T. Kohonen, M. Mäkisara, O. Simula, and J. Kangas (Eds.), **Artificial neural networks, Volume 1**. Amsterdam: Elsevier, pp. 3–8. (*#&)

63. Grossberg, S. and Somers, D. (1992). Synchronized oscillations for binding spatially distributed feature codes into coherent spatial patterns. In G.A. Carpenter and S. Grossberg (Eds.), **Neural networks for vision and image processing**. Cambridge, MA: MIT Press, pp. 385–406. (*#&)

64. Grossberg, S. and Somers, D. (1992). Synchronized oscillations for binding spatially distributed features into preattentive and attentive brain representations. In M. Marinaro and G. Scarpetta (Eds.), **Structure: From physics to general systems**. Singapore: World Scientific Publishing Company, 2, 95–112. (#&@)

65. Grossberg, S. and Wyse, L. (1991). Invariant recognition of cluttered scenes by a self-organizing ART architecture: Figure-ground separation. *Neural Networks*, **4**, 723–742. (*#=)

66. Grossberg, S. and Wyse, L. (1991). Invariant recognition of cluttered scenes by a self-organizing ART architecture: Figure-ground separation. In **Proceedings of the international joint conference on neural networks**, Seattle, **I**, 633–638. Piscataway, NJ: IEEE Service Center. (*#=)

67. Grossberg, S. and Wyse, L. (1992). A neural network architecture for figure-ground separation of connected scenic figures. In R.B. Pinter and B. Nabet (Eds.), **Nonlinear vision: Determination of neural receptive fields, function, and networks**. Boca Raton, FL: CRC Press. (*#=)

68. Grossberg, S. and Wyse, L. (1992). Figure-ground separation of connected scenic figures: Boundaries, filling-in, and opponent processing. In G.A. Carpenter and S. Grossberg (Eds.), **Neural networks for vision and image processing**. Cambridge, MA: MIT Press, pp. 161–194. (*#=)

69. Lesher, G.W. and Mingolla, E. (1993). The rôle of edges and line-ends in illusory contour formation. *Vision Research*, **33**, 2253-2270. (+@)

70. Lesher, G.W. and Mingolla, E. (1994). Neural models of illusory contour formation. In M.A. Arbib (Ed.), **Handbook of brain theory and neural networks.** Cambridge, MA: MIT Press, in press. (+@)

71. Mingolla, E. (1991). Neural dynamics of static and motion visual segmentation. In R. Plamondon and E.H.D. Chang (Eds.), **Pattern recognition: Architectures, algorithms, and applications.** Singapore: World Scientific Publishers.

72. Mingolla, E. (1991). Neural dynamics of motion segmentation and grouping. Invited article in R. Lippmann, J. Moody, and D.S. Touretsky (Eds.), **Advances in neural information processing systems.** San Diego: Morgan Kaufman.

73. Mingolla, E. and Gaudiano, P. (1992). Dinamica neurale della percezione visiva. *Sistemi Intelligenti*, **IV**, 75-99.

74. Mingolla, E., Todd, J.T., and Norman, J.F. (1992). The perception of globally coherent motion. *Vision Research*, **32**, 1015-1031.

*	Also supported in part by the Army Research Office (expired)
#	Also supported in part by ARPA
%	Also supported in part by British Petroleum (nonrenewable)
=	Also supported in part by the Hughes Research Labs (expired)
&	Also supported in part by NASA (expired)
+	Also supported in part by the National Science Foundation (expired)
@	Also supported in part by the Office of Naval Research

V. BOSTON UNIVERSITY PROJECT SUMMARIES

1. Supervised and Unsupervised Learning, Recognition, and Prediction of Nonstationary Analog Data Bases [Articles 8–12,14–26]

As we move freely through the world, we can attend to both familiar and novel objects, and can rapidly learn to recognize, test hypotheses about, and learn to name novel objects without unselectively disrupting our memories of familiar objects. This article describes a new self-organizing neural network architecture—called a Fuzzy ARTMAP—that is capable of fast, yet stable, on-line recognition learning, hypothesis testing, and adaptive naming in response to an arbitrary stream of analog or binary input patterns.

The Fuzzy ARTMAP architecture combines a set of computational properties (Table 1) whose unavailability in alternative approaches have limited their ability to function autonomously in a rapidly changing world. Indeed, it represents a computational synthesis of ideas from neural networks, production systems, and fuzzy logic. These properties enable Fuzzy ARTMAP to autonomously learn, recognize, and make predictions about:

(A) Rare Events

A successful autonomous agent must be able to learn about rare events that have important consequences, even if these rare events are similar to a surrounding cloud of frequent events that have different consequences (Figure 1). *Fast learning* is needed to pick up a rare event on the fly. For example, a rare medical case may be the harbinger of a new epidemic. A faint astronomical signal may signify important consequences for theories of the Universe. A slightly different chemical assay may predict the biological activity of a new drug. Many traditional learning schemes use a form of slow learning that tends to average over similar event occurrences. In contrast, Fuzzy ARTMAP can rapidly learn a rare event that predicts different consequences than a cloud of similar events in which it is embedded.

(B) Large Nonstationary Data Bases

Rare events typically occur in a nonstationary environment whose event statistics may change rapidly and unexpectedly through time. Individual events may also occur with variable probabilities and durations, and arbitrarily large numbers of events may need to be processed. Each of these factors tends to destabilize the learning process within traditional algorithms. New learning in such algorithms tends to unselectively wash away the memory traces of old, but still useful, knowledge. Using such an algorithm, for example, learning a new face could erase the memory of a parent's face. More generally, learning a new type of expertise could erase the memory of previous expert knowledge. Fuzzy ARTMAP contains a *self-stabilizing memory* that permits accumulating knowledge to be stored reliably in response to arbitrarily many events in a nonstationary environment under incremental learning conditions, until the algorithm's full memory capacity, which can be chosen arbitrarily large, is exhausted.

(C) Morphologically Variable Types of Events

In many environments, some information is coarsely defined whereas other information is precisely characterized. Otherwise expressed, the morphological variability of the data may change through time. For example, it may just be necessary to recognize that an object is an animal, or you may need to confirm that it is your own pet. It may just be necessary to

AUTONOMOUS LEARNING AND CONTROL IN A NONSTATIONARY WORLD

Need one system that reconciles conflicting properties -
a system that can autonomously learn about:

(A) RARE EVENTS
- need FAST learning

(B) LARGE NONSTATIONARY DATABASES
- need STABLE learning

(C) MORPHOLOGICALLY VARIABLE EVENTS
- need MULTIPLE SCALES of generalization (fine/coarse)

(D) ONE-TO-MANY AND MANY-TO-ONE RELATIONSHIPS
- need categorization, naming, and expert knowledge

To realize these properties, ARTMAP systems:

(E) PAY ATTENTION
- ignore masses of irrelevant data

(F) TEST HYPOTHESES
- discover predictive constraints hidden in data streams

(G) CHOOSE BEST ANSWERS
- quickly select globally optimal solution at any stage of learning

(H) CALIBRATE CONFIDENCE
- measure on-line how well a hypothesis matches the data

(I) DISCOVER RULES
- identify transparent IF-THEN relations at each learning stage

(J) SCALE
- preserve all desirable properties in arbitrarily large problems

Table 1.

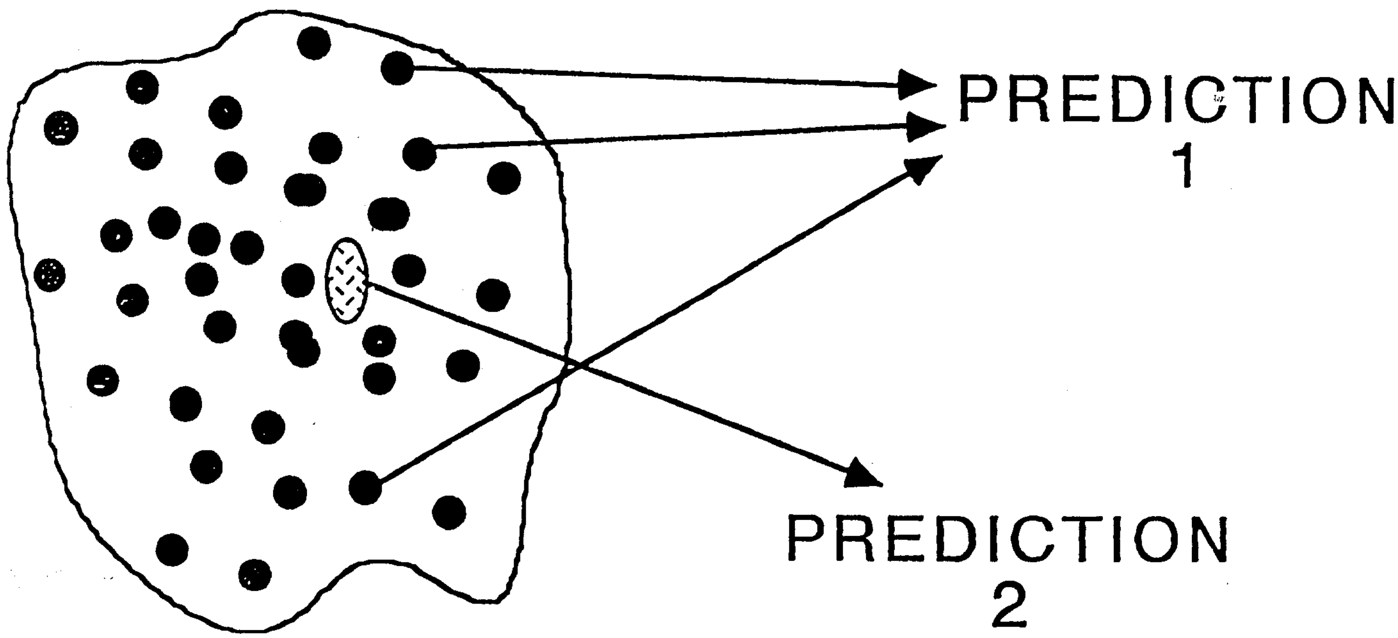


Figure 1. Fuzzy ARTMAP can learn a different prediction for a rare event than for all the similar events that surround it.

recognize that an object is an airplane, or that it is a particular type of airplane that is flown for a particular purpose by a particular country. Under autonomous learning conditions, no teacher is typically available to instruct a system about how coarse its generalization, or compression, of particular types of data should be. Multiple scales of generalization, from fine to coarse, need to be available on an as-needed basis. Fuzzy ARTMAP is able to automatically adjust its scale of generalization to match the morphological variability of the data. It embodies a Minimax Learning Rule that conjointly *min*imizes predictive error and *max*imizes generalization using only information that is locally available under incremental learning conditions in a nonstationary environment.

(D) Many-to-One and One-to-Many Relationships

Many-to-one learning takes two forms: categorization and naming (Figure 2). For example, during categorization of printed letter fonts, many similar exemplars of the same printed letter may establish a single recognition category, or compressed representation. Different printed letter fonts or written exemplars of the letter may establish additional categories. Each of these categories carries out a many-to-one map of exemplar into category. During naming, all of the categories that represent the same letter may be associatively mapped into the letter name, or prediction. This is a second, distinct, type of many-to-one map. There need be no relationship whatsoever between the visual features that define a printed letter A and a written letter A, yet both categories may need to be assigned the same name due to cultural, not visual, reasons.

One-to-many learning is used to build up expert knowledge about an object or event (Figure 3). A single visual image of a particular animal may, for example, lead to learning that predicts: animal, dog, beagle, and my dog "Rover". A computerized record of a patient's medical check-up may lead to a series of predictions about the patient's health. A chemical assay of a sample of coal or petroleum may lead to many predictions about its uses as an energy source or structural material. In many learning algorithms, the attempt to learn more than one prediction about an event leads to unselective forgetting of previously learned predictions, for the same reason that these algorithms become unstable in response to nonstationary data.

Error-based learning systems, including the popular back propagation algorithm, find it difficult, if not impossible, to achieve any of the computational goals (A)–(D). Back propagation compares its actual prediction with a correct prediction and uses the error to change adaptive weights in a direction that is error-reducing. Fast learning would zero the error on each learning trial, and therefore cause massive forgetting. Statistical changes in the environment drag the adaptive weights away from their estimates of the previous environment. Longer event durations zero the error more, and thereby destabilize previous memories for the same reason that fast learning does. The selection of a fixed number of hidden units tends to fix a uniform level of generalization. Error-based learning also tends to force forgetting of previous predictions under one-to-many learning conditions, because the present correct prediction treats all previously learned predictions as errors. Ratcliff (1990) has noted, moreover, that back propagation fails to simulate human cognitive data about learning and forgetting.

Fuzzy ARTMAP exhibits the properties (A)–(D) because it implements a qualitatively different set of heuristics than error-based learning systems. These heuristics are embodied in the following types of processes:

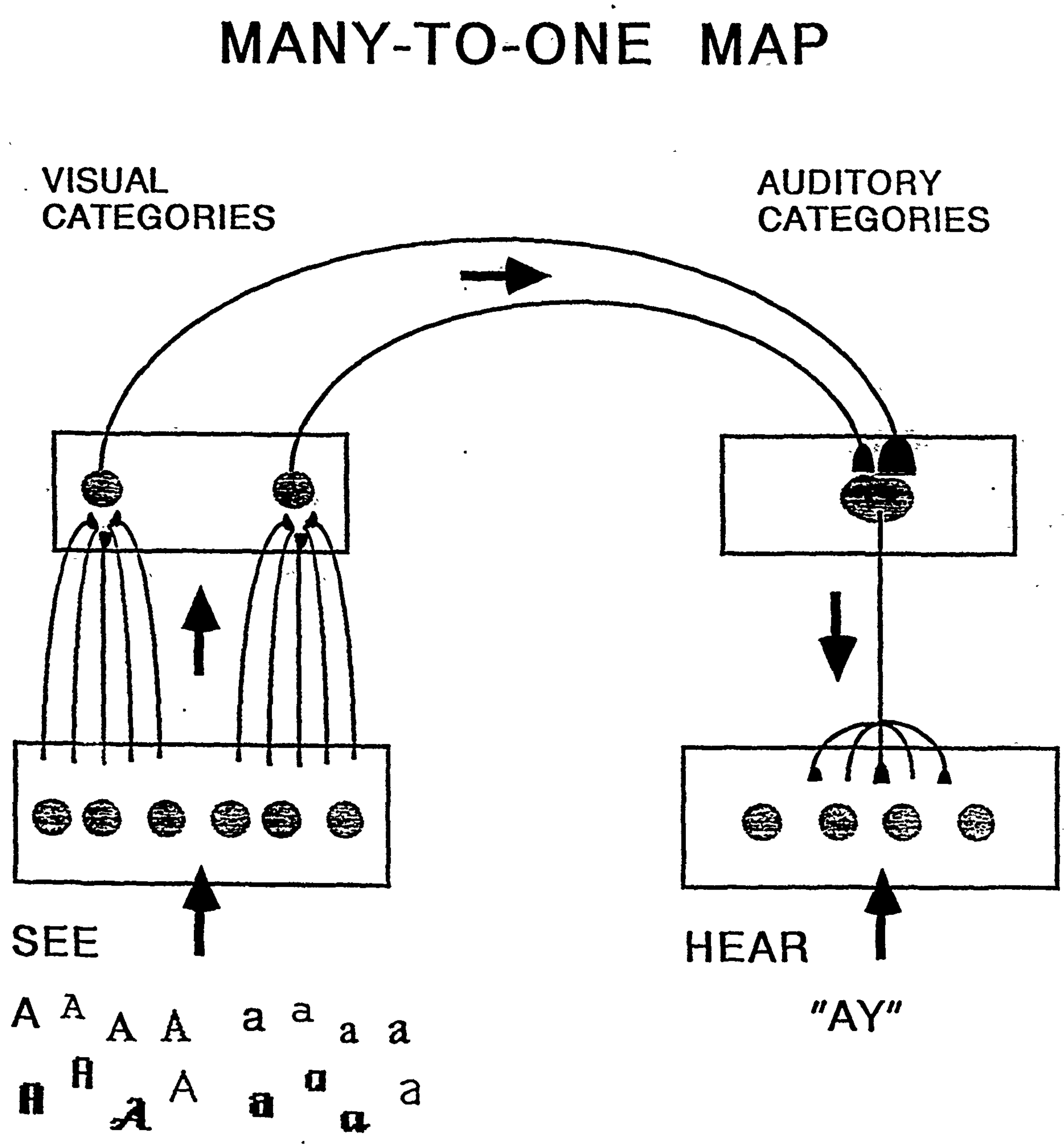


Figure 2. Many-to-one learning combines categorization of many exemplars into one category, and labelling of many categories with the same name.

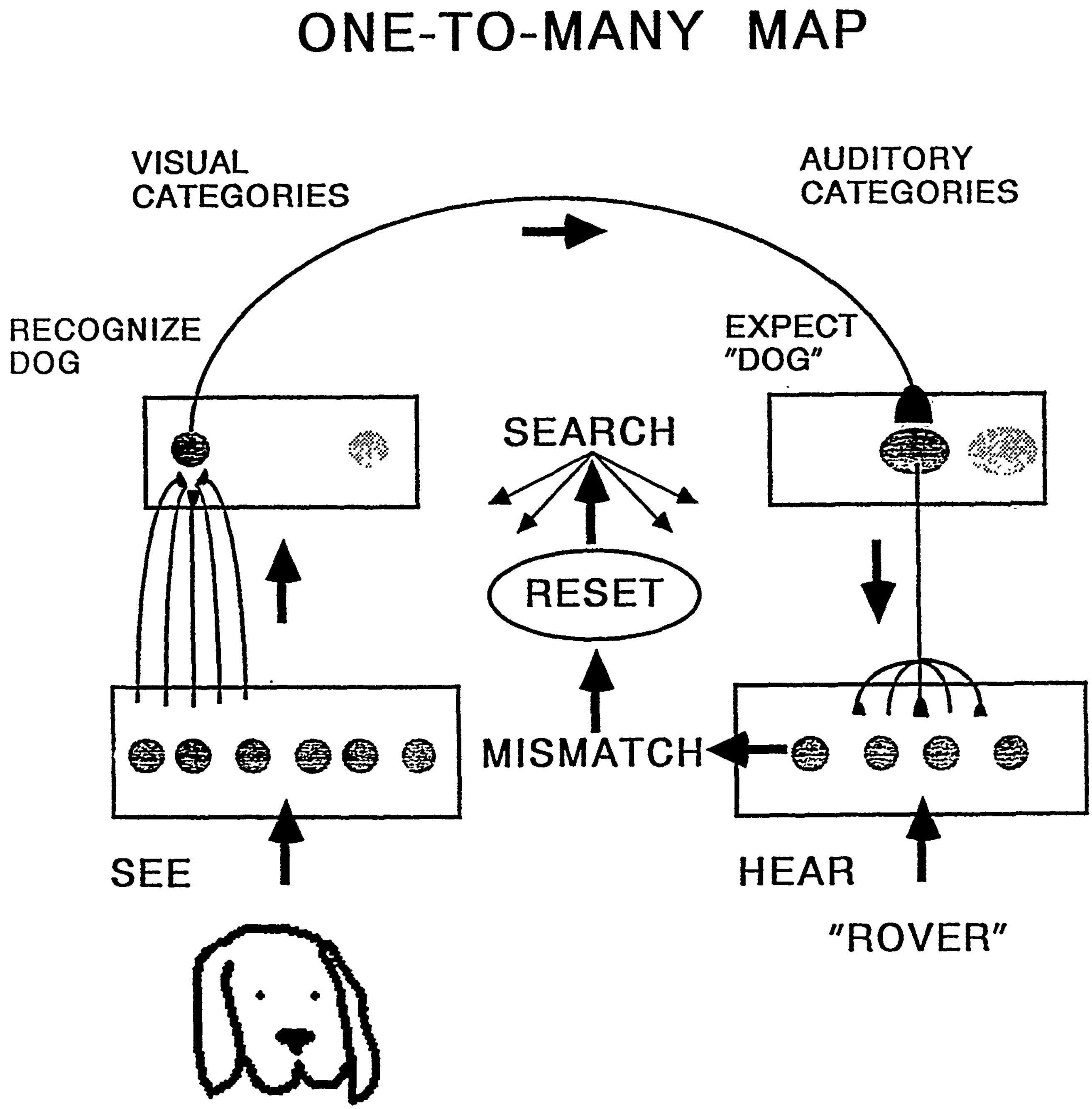


Figure 3. One-to-many learning enables one input vector to be associated with many output vectors. If the system predicts an output that is disconfirmed at a given stage of learning, the predictive error drives a memory search for a new category to associate with the new prediction, without degrading its previous knowledge about the input vector.

(E) Pay Attention

A Fuzzy ARTMAP system can learn top-down expectations (also called primes, or queries) that can bias the system to ignore masses of irrelevant data. A large mismatch between a bottom-up input vector and a top-down expectation can drive an adaptive memory search that carries out

(F) Hypothesis Testing and Match-Based Learning

The system actively searches for recognition categories, or hypotheses, whose top-down expectations provide an acceptable match to bottom-up data. The top-down expectation focuses attention upon, and binds, that cluster of input features that it deems to be relevant. If no available category, or hypothesis, provides a good enough match, then selection and learning of a new category and top-down expectation is automatically initiated. When the search discovers a category that provides an acceptable match, the system locks into an attentive resonance whereby the input exemplar refines the adaptive weights of the category based on any new information that it contains.

Thus the Fuzzy ARTMAP system carries out match-based learning, rather than error-based learning. A category modifies its previous learning only if its top-down expectation matches the input vector well enough to risk changing its defining characteristics. Otherwise, hypothesis testing selects a new category on which to base learning of a novel event.

(G) Choose Globally Best Answer

In many learning algorithms, as learning proceeds, local minima or less than optimal solutions are selected to represent the data. In Fuzzy ARTMAP, at any stage of learning, an input exemplar first selects the category whose top-down expectation provides the globally best match. A top-down expectation hereby acts as a *prototype* for the class of all the input exemplars that its category represents. After learning self-stabilizes, every input directly selects the globally best category without any search. Before learning self-stabilizes, familiar events gain direct access to the globally best category without any search, even if they are interspersed with unfamiliar events that drive hypothesis testing for better matching categories.

(H) Calibrate Confidence

A confidence measure, called *vigilance*, calibrates how well an exemplar matches the prototype that it selects. Otherwise expressed, vigilance measures how well the chosen hypothesis matches the data. If vigilance is low, even poor matches are accepted. Many different exemplars can then be incorporated into one category, so compression and generalization by that category are high. If vigilance is high, then even good matches may be rejected, and hypothesis testing may be initiated to select a new category. In this case, few exemplars activate the same category, so compression and generalization are low. A very high vigilance can select a unique category for a rare event that predicts an outcome different from that of any of the similar exemplars that surround it.

The Minimax Learning Rule is realized by adjusting the vigilance parameter in response to a predictive error. Vigilance is increased just enough to initiate hypothesis testing to discover a better category, or hypothesis, with which to match the data. In this way, a minimum amount of generalization is sacrificed to correct the error. This process is called *match tracking* because vigilance tracks the degree of match between exemplar and prototype in response to a predictive error.

(I) Rule Extraction

At any stage of learning, a user can translate the state of a Fuzzy ARTMAP system into an algorithmic set of IF-THEN rules. From this perspective, Fuzzy ARTMAP can be interpreted as a type of self-organizing expert system. These rules evolve as the system is exposed to new inputs. This feature is particularly important in applications such as medical diagnosis from a large database of patient records. Table 2 summarizes some medical and other benchmark studies that compare the performance of Fuzzy ARTMAP with alternative recognition and prediction models.

(J) Properties Scale

One of the most serious deficiencies of many Artificial Intelligence algorithms is that their desirable properties tend to break down as small toy problems are generalized to large-scale problems. In contrast, all of the desirable properties of Fuzzy ARTMAP scale to arbitrarily large problems. It must be emphasized, however, that Fuzzy ARTMAP solves a particular type of problem. It is not intended to solve all problems of learning or intelligence. The categorization and prediction problems that ARTMAP does handle well are, however, core problems in many intelligent systems, and have been technology bottlenecks for many alternative approaches.

In summary, as Tables 1 and 2 illustrate, the Fuzzy ARTMAP family of architectures embody many insights from cognitive psychology into a neural network algorithm which is proving to be consistently superior to symbolic machine learning, genetic algorithm, and alternative neural network architectures. This superiority reflects itself in fundamental system properties, such as being able to learn about large nonstationary databases with which other models cannot cope, as well as in greater accuracy and much faster learning on standard benchmark problems.

These supervised ART systems are also being applied to explain clinial data about medial temporal amnesia due to lesions of the hippocampal formation, and data about normal recognition learning by inferotemporal cortex. New predictions are also being developed about how the hippocampal formation may regulate the specificity of the recognition codes that are learned by inferotemporal cortex. Several neurobiology labs have accordingly begun to use the theory to analyse their neurobiological data about inferotemporal cortex; e.g., Desimone's lab at NIMH and Gochin's lab at Princeton.

2. 3-D Vision and Figure-Ground Separation by Visual Cortex [Articles 47–49]

A theory of 3-D visual perception and figure-ground separation by visual cortex has been described. A solution of the classical figure-ground problem for biological vision is developed within the theory. A unified explanation is given of how a 2-D image may generate a 3-D percept; how figures pop-out from cluttered backgrounds; how spatially sparse disparity cues can generate continuous surface representations at different perceived depths; how binocular fusion of objects at different depths can deform perceptual space by different amounts, as during allelotropia; how representations of occluded regions can be completed and recognized without usually being seen; how occluded regions can sometimes be seen during percepts of transparency; how high spatial frequency parts of an image may appear closer than low spatial frequency parts; how sharp targets are detected better against a figure and blurred targets are detector better against a background; how low spatial frequency parts of an image may be fused while high spatial frequency parts are rivalrous; how sparse blue cones

ARTMAP BENCHMARK STUDIES

1. Medical database - mortality following coronary bypass grafting (CABG) surgery

   FUZZY ARTMAP significantly outperforms:

   LOGISTIC REGRESSION

   ADDITIVE MODEL

   BAYESIAN ASSIGNMENT

   CLUSTER ANALYSIS

   CLASSIFICATION AND REGRESSION TREES

   EXPERT PANEL-DERIVED SICKNESS SCORES

   PRINCIPAL COMPONENT ANALYSIS

2. Mushroom database

   DECISION TREES (90-95 % correct)

   ARTMAP (100% correct)
   Training set an order of magnitude smaller

3. Letter recognition database

   GENETIC ALGORITHM (82% correct)

   FUZZY ARTMAP (96% correct)

4. Circle-in-the-Square task

   BACK PROPAGATION (90% correct)

   FUZZY ARTMAP (99.5% correct)

5. Two-Spiral task

   BACK PROPAGATION (10,000 - 20,000 training epochs)

   FUZZY ARTMAP (1-5 training epochs)

Table 2.

can generate vivid blue surface percepts; how depth attraction may occur between nearby targets and depth repulsion between further targets; how 3-D neon color spreading, visual phantoms, and tissue contrast percepts are generated; how conjunctions of color-and-depth may rapidly pop-out during visual search. These explanations are derived from an ecological analysis of how monocularly viewed parts of an image inherit the appropriate depth from contiguous binocularly viewed parts, as during DaVinci stereo, the equidistance tendency, and the viewing of texture stereograms.

Such data analyses have led to a neural theory of how the two parvocellular processing streams that join LGN to prestriate area V4. interact to generate a multiplexed representation of Form-And-Color-And DEpth, or FACADE, within area V4. The two parvocellular streams are modelled by a Boundary Contour System (BCS) and a Feature Contour System (FCS). The BCS generates emergent boundary segmentations that combine edge, texture, shading, and stereo information. The FCS discounts the illuminant and fills-in surface properties of brightness, color, and depth. The ensemble of all surface representations constitutes the FACADE representation. The BCS and FCS interact reciprocally via adaptive filters with an Object Recognition System, interpreted to occur in inferotemporal cortex, to bind these segmentation and surface properties together. It is shown how interactions between BCS and FCS, especially partially ordered interactions form larger scales and disparities to smaller scales and disparities, inhibit spurious boundary and surface signals.

Key new ideas are that filled-in connected regions at a given disparity inhibit the boundaries and features of smaller disparity representations; near-zero disparity cell pools and non-zero disparity cell pools interact to generate boundary segmentations; the cortical magnification factor helps to convert different disparity computations at different foveal eccentricities into a planar surface representation; multiple receptive field sizes cooperate to generate positionally accurate segmentations, and to suppress low spatial frequency contributions at high curvature contours; double-opponent networks react to boundary-gated filling-in events by selecting binocularly consistent combinations of monocular featural data, and suppressing inconsistent data; ocular dominance columns control the amount of allelotropia and the size-disparity correlation that decide between binocular fusion and rivalry; self-similar networks of simple cells, complex cells, hypercomplex cells, higher-order hypercomplex cells, and bipole cells generate hyperacute boundary segmentations that organize surface representations into ecologically useful 3-D percepts.

In summary, this work promises to represent a major breakthrough in our understanding of the principles and mechanisms of the visual cortex whereby humans and other mammals perceive a 3-D world. The potential biological importance of the theory is calibrated by the size of the perceptual and neural databases for which it, but no other available theory, provides a unified explanation. The potential applications in machine vision are also extensive, especially for the processing of noisy and ambiguous images wherein it is difficult for other algorithms to define, or "pop out," object representations. This machine vision potential gains credibility from the fact that earlier versions of the theory are already being implemented in the processing of laser radar, synthetic aperture radar, infrared, magnetic resonance, and high-altitude photographic images [e.g., articles 65–68].

3. Cortical Dynamics of Feature Binding and Reset: Control of Visual Persistence [Articles 36–38]

The ability to rapidly reset segmentations in order to avoid undue *smearing* is of crucial importance to any real-time vision system. Mammalian systems have evolved ingenious specializations to address this problem. Francis, Grossberg, and Mingolla hypothesize that many properties of visual persistence are caused by positive feedback in the visual cortical circuits that are responsible for the binding or segmentation of visual features into coherent visual forms, and that the degree of persistence is limited by circuits that reset these segmentations at stimulus offset. They propose a model of the cortical local circuitry responsible for such feature binding and reset, and use the model to quantitatively simulate psychophysical data showing increase of persistence with spatial separation of a masking stimulus; inverse relation of persistence to flash luminance and duration; greater persistence of illusory contours than real contours, with maximal persistence at an intermediate stimulus duration; and dependence of persistence on pre-adapted stimulus orientation. The model is a refinement of the BCS architecture, whereby the dynamics of relatively slowly varying transmitter gates are embedded into the Cooperative-Competitive Loop (CC Loop) of the Boundary Contour System (BCS). The transmitter gates form *gated dipoles* that instantiate the opponent inhibition across cells tuned to perpendicular orientations at the second competitive stage of the BCS (see Figures 4 and 5). As a result, the model proposed by Francis, Grossberg, and Mingolla is compatible with existing implementations of the BCS for image processing applications, and provides a principled basis for extending BCS segmentation procedures to time-varying imagery.

4. Modeling Cortical Dynamics of Coherent Motion Processing [Articles 51–54]

Grossberg and Mingolla have extended earlier work on motion perception by the CAS group. In their article, a neural network model of global motion segmentation by visual cortex is described. Called the Motion Boundary Contour System (BCS), the model clarifies how ambiguous local movements on a complex moving shape are actively reorganized into a coherent global motion signal. Unlike many previous researchers, they analyse how a coherent motion signal is imparted to all regions of a moving figure, not only to regions at which unambiguous motion signals exist. The model thereby suggests a solution to the global aperture problem. The Motion BCS describes how preprocessing of motion signals by a Motion Oriented Contrast Filter (MOC Filter) is joined to long-range cooperative grouping mechanisms in a Motion Cooperative-Competitive Loop (MOCC Loop) to control phenomena such as motion capture. The Motion BCS is computed in parallel with the Static BCS of Grossberg and Mingolla (1985a, 1985b, 1987). Homologous properties of the Motion BCS and the Static BCS, specialized to process movement directions and static orientations, respectively, support a unified explanation of many data about static form perception and motion form perception that have heretofore been unexplained or treated separately. Predictions about microscopic computational differences of the parallel cortical streams $V1 \rightarrow MT$ and $V1 \rightarrow V2 \rightarrow MT$ are made, notably the magnocellular thick stripe and parvocellular interstripe streams. It is shown how the Motion BCS can compute motion directions that may be synthesized from multiple orientations with opposite directions-of-contrast. Interactions of model simple cells, complex cells, hypercomplex cells, and bipole cells are described, with special emphasis given to new functional roles in direction disambiguation for endstopping at multiple processing stages and to the dynamic interplay of spatially short-range and

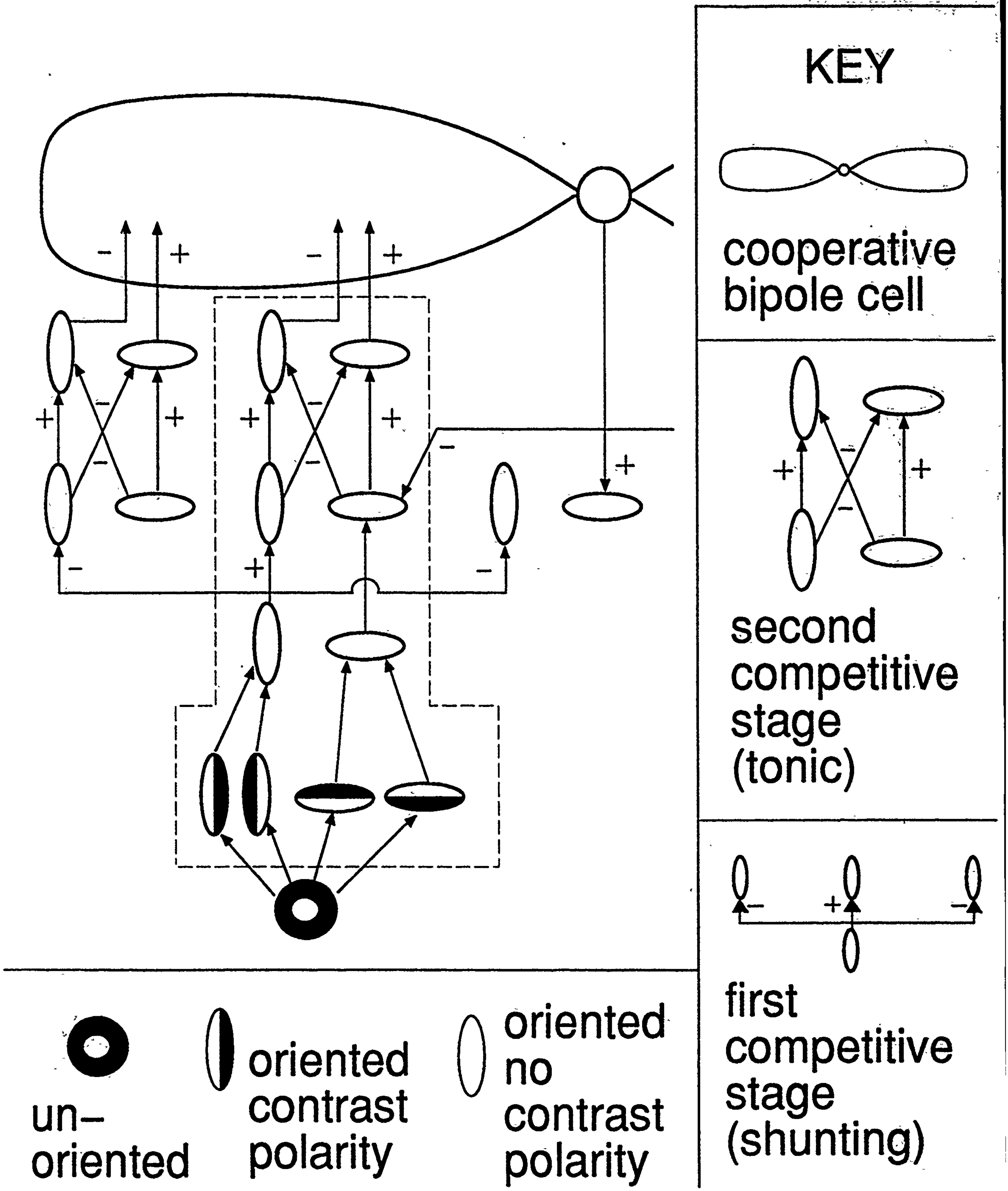


Figure 4. The Boundary Contour System.

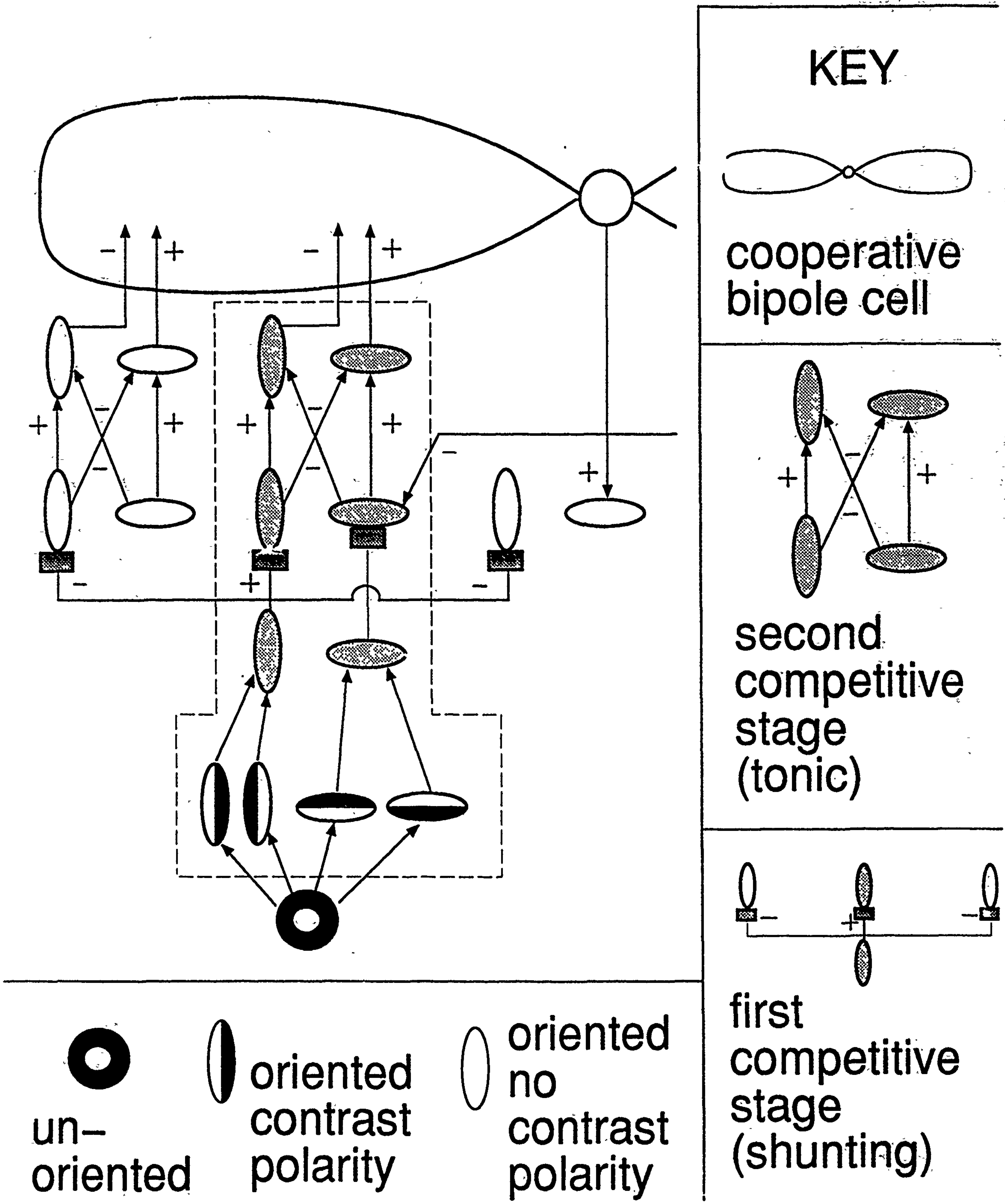


Figure 5. The Boundary Contour System with embedded gated dipole field.

long-range interactions.

The work on motion segmentation dovetails with the work on visual persistence (Section 3) to clarify how *both* the static form and motion form systems in primate vision can react to the same moving input to provide complementary and cooperative measures of moving form. Thus, while for extreme parameter ranges (i.e., perfectly still images, or "blindingly" fast motion) only one of the form systems may operate effectively, there exist important intermediate cases in which both can produce valid segmentations whose results can be compared. The more sophisticated segmentations of the Static BCS can be used to enhance perception of motion in complex or cluttered scenes (e.g., movement of "illusory contours") and the rapid assessment of direction-of-motion afforded by the Motion BCS can be used to rapidly direct eye movements or attention to important regions of the scene for more thorough processing.

5. Perceptual Experiments on Globally Coherent Motion [Article 74]

In collaboration with Jim Todd and Farley Norman, while they were at Brandeis University, Ennio Mingolla conducted psychophysical investigations on the perception of globally coherent motion. Their study asked: How do human observers perceive a coherent pattern of motion from a disparate set of local motion measures? Their research examined how ambiguous motion signals along straight contours are spatially integrated to obtain a globally coherent perception of motion. Observers viewed displays containing a large number of apertures, with each aperture containing one or more contours whose orientations and velocities could be independently specified. The total pattern of the contour trajectories across the individual apertures was manipulated to produce globally coherent motions, such as rotations, expansions, or translations. For displays containing only straight contours extending to the circumferences of the apertures, observers' reports of global motion direction were biased whenever the sampling of contour orientations was asymmetric relative to the direction of motion. Performance was improved by the presence of identifiable features, such as line ends or crossings, whose trajectories could be tracked over time. The reports of the observers were consistent with a pooling process involving a vector average of measures of the component of velocity normal to contour orientation, rather than with the predictions of the intersection-of-constraints analysis in velocity space. This psychophysical work was directly related to the vision modeling work at the CAS, insofar as it provided empirical evidence for a vector averaging process in motion perception along the lines suggested by the work of Grossberg and Mingolla described in Section 4.

6. Multiscale Neural Network Processing of Synthetic Aperture Radar Images [Article 57]

A multiscale image processing algorithm (Figures 6 and 7) based on the Boundary Contour System (BCS) and Feature Contour System (FCS) neural network models of preattentive vision, developed at Boston University's Center for Adaptive Systems and Department of Cognitive and Neural Systems, has been transferred to MIT's Lincoln Laboratory and applied to large images containing range data gathered by a synthetic aperture radar (SAR) sensor. Researchers at Lincoln Laboratory have in turn supplied enhanced versions of that software to clients at other laboratories. The goal of the algorithm is to make structures such as motor vehicles, roads, or buildings more salient and more interpretable to human observers than they are in the original imagery. Early automatic gain control by shunting center-surround networks compresses signal dynamic range while performing local contrast enhancement. Subsequent processing by filters sensitive to oriented contrast, including short-range competition and long-range cooperation, segments the image into regions. The segmentation is performed by three "copies" of the BCS and FCS, of small, medium, and large scales, wherein the "short-range" and "long-range" interactions within each scale occur over smaller or larger image distances, corresponding to the size of the early filters of each scale. Finally, a diffusive filling-in operation within the segmented regions generates surface representations of visible structures. The combination of BCS and FCS helps to locate and enhance structure over regions of many pixels, without the resulting blur characteristic of approaches based on low spatial frequency filtering alone.

7. Visual Search: Modeling How Humans Rapidly Detect Targets in Clutter [Article 56]

Visual search data were given a unified quantitative explanation by a model of how spatial maps in the parietal cortex and object recognition categories in the inferotemporal cortex deploy attentional resources as they reciprocally interact with visual representations in the prestriate cortex. The model visual representations are organized into multiple boundary and surface representations. Visual search in the model is initiated by organizing multiple items that lie within a given boundary or surface representation into a candidate search grouping. These items are compared with object recognition categories to test for matches or mismatches. Mismatches can trigger deeper searches and recursive selection of new groupings until a target object is identified. This search model is algorithmically specified to quantitatively simulate search data using a single set of parameters, as well as to qualitatively explain a still larger data base, including data of Aks and Enns (1992), Bravo and Blake (1990), Chellazzi, Miller, Duncan, and Desimone (1993), Egeth, Virzi, and Garbart (1984), Cohen and Ivry (1991), Enns and Rensink (1990), He and Nakayama (1992), Humphreys, Quinlan, and Riddoch (1989), Mordkoff, Yantis, and Egeth (1990), Nakayama and Silverman (1986), Treisman and Gelade (1980), Treisman and Sato (1990), Wolfe, Cave, and Franzel (1989), and Wolfe and Friedman-Hill (1992). The model hereby provides an alternative to recent variations on the Feature Integration and Guided Search models, and grounds the analysis of visual search in neural models of preattentive vision, attentive object learning and categorization, and attentive spatial localization and orientation.

8. Perception of Illusory Contours: Human Psychophysical Experiments to Test and Constrain Development for Projects 2 and 6 [Article 69]

Lesher and Mingolla (1993) showed that illusory contours can be induced along directions approximately collinear to edges or approximately perpendicular to the ends of lines. Using a rating scale procedure, they explored the relation between the two types of inducers by systematically varying the thickness of inducing elements to result in varying amounts of "edge-like" or "line-like" induction. Inducers for the illusory figures consisted of concentric rings with arcs missing. Observers judged the clarity and brightness of illusory figures as the number of arcs, their thicknesses, and spacing were parametrically varied. Degree of clarity and amount of induced brightness were both found to be inverted-U functions of the number of arcs. These results mandate that any valid model of illusory contour formation must account for interference effects between parallel lines or between those neural units responsible

Single-Scale BCS/FCS Model

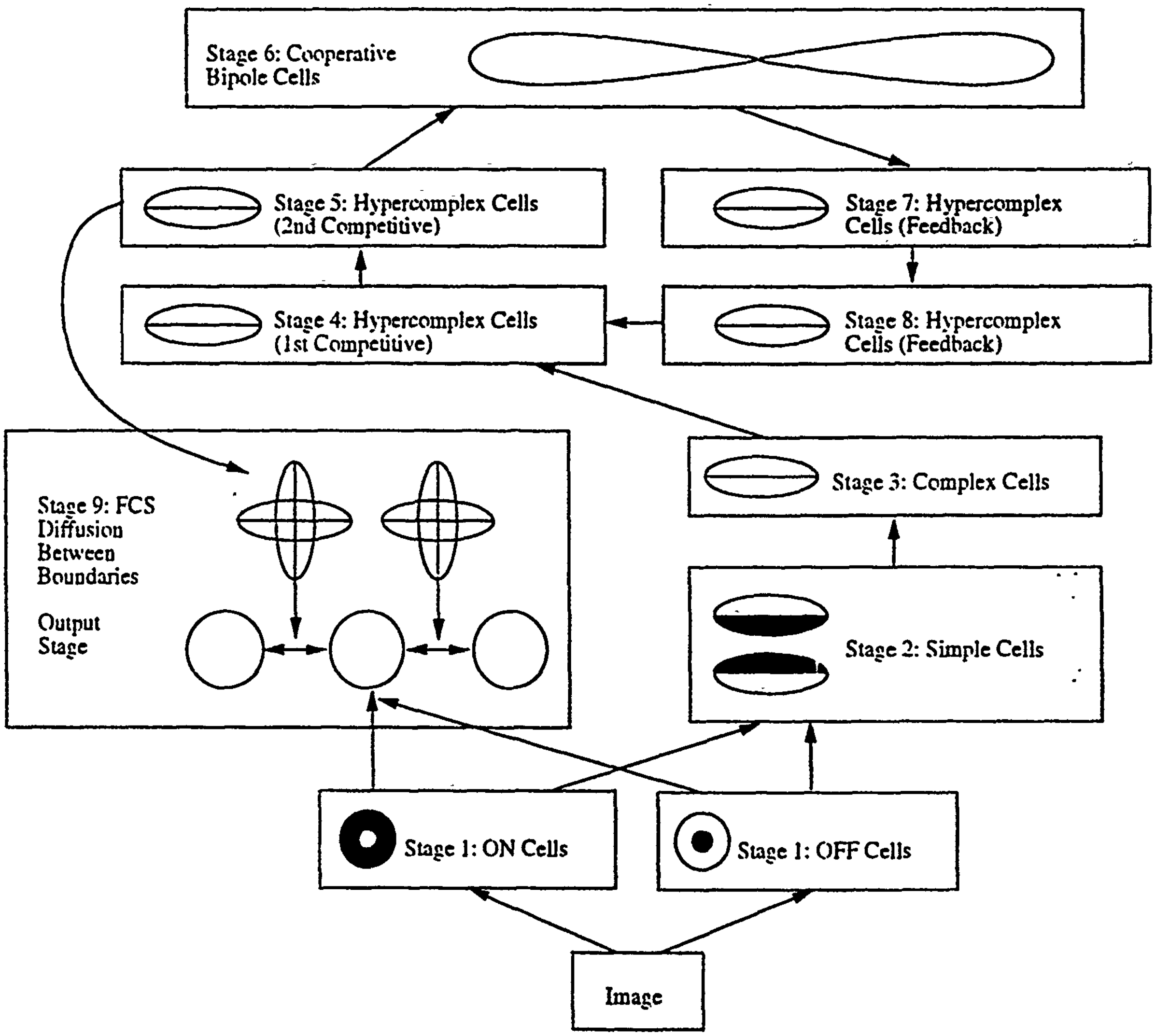
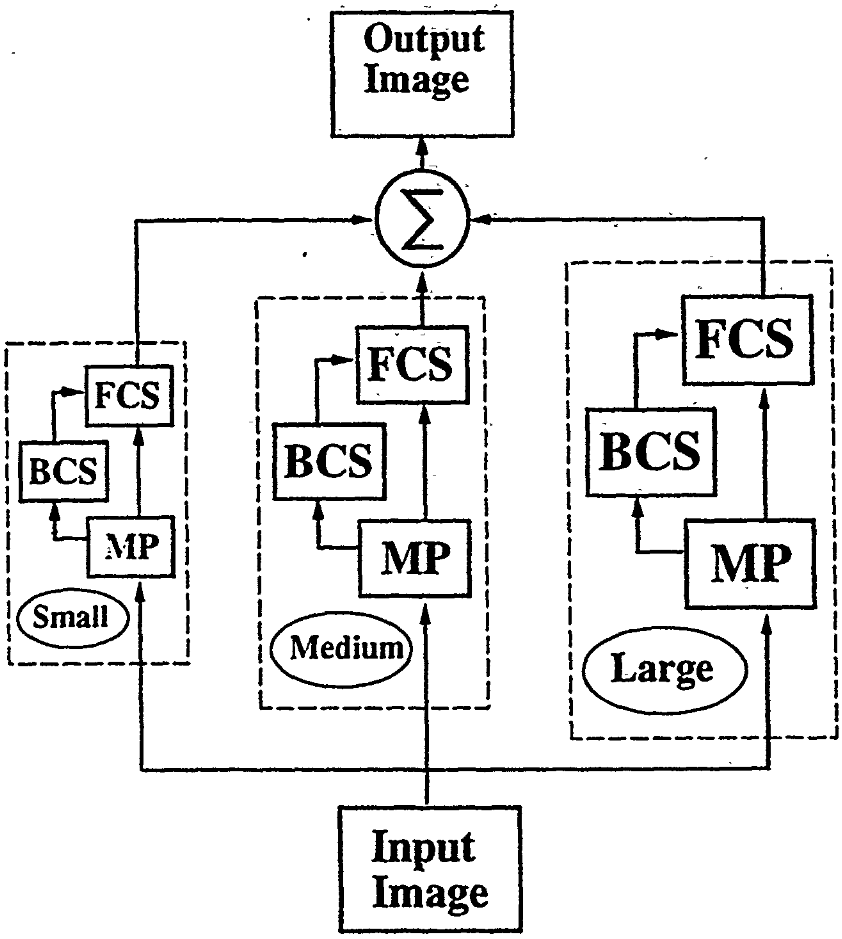


Figure 6. A single scale of processing in the BCS/FCS model.

Multiple–Scale BCS/FCS Model



MP = Monocular Preprocessing
BCS = Boundary Contour System
FCS = Feature Contour System

Figure 7. A multiple scale BCS/FCS model.

for completion of boundary signals in directions perpendicular to the ends of thin lines. Line width was found to have an effect on both clarity and brightness, a finding inconsistent with those models which employ *only* completion perpendicular to inducer orientation. Subsequent research by Lesher, Grossberg, and Mingolla reported in Lesher (1993) showed that the Static BCS could fit the data of the Lesher and Mingolla (1993) experiment.

9. Transient Processing by Early Motion Mechanisms

In collaborative research with Grossberg and Mingolla, the Nogueira (1993) doctoral research developed a neural network model of visual motion detection based on primate physiology and human behavioral data. Unlike many computational approaches to motion detection, the model receives inputs only from transient cells that are sensitive to changes in luminance in accordance with key physiological data. The model includes analogs of properties known to exist in the primate visual system, such as segregation of ON and OFF channels and center-surround, spatially antagonistic input processing. The model behaves in accordance with human perceptual data in several paradigms, including first-order motion, second-order motion, drift-balanced motion, and the Chubb and Sperling gamma display. First-order motion, for example, is defined by stimuli whose motion can be detected by spatial correlation of the changes in mean luminance over time. Simulation results of first-order motion are also in accordance with monkey physiological data, suggesting that coherent dot motion can be detected using only transient (magnocellular) cell detectors. The existence of two independent model changes (lightening and darkening) explains why certain cortical directionally selective cells detect the motion of luminance edges with one polarity in one direction and the other polarity in the reverse direction when response from retinal ON cells are pharmacologically blocked.

10. Corticogeniculate Feedback: Modeling Its Role in Boundary Localization and Brightness Perception

The Gove (1993) dissertation describes joint research with Grossberg and Mingolla on development of the BCS and FCS using psychophysical data concerning the perception of illusory contours, including the formation of contours, the separability of contour salience and brightness effects, and line end contrast. The present work provides computational demonstrations of the theory's competence in modeling several important illusory contour phenomena. A key extension is the addition of a stage corresponding to the lateral geniculate nucleus (LGN), which uses cortical feedback to enhance contrast at line ends and which forms a model analog of perceptually enhanced brightness at line ends or corners. A key functional role for such feedback is binocular matching monocular LGN activations with binocular top-down cortical feedback. The simulated effects result. Simulations are done on synthetic images of illusory contour stimuli, and the results are compared to data on human judgments of the boundary sharpness and brightness enhancement of similar displays. The enhanced model is also used to simulate perceptual grouping effects, such as those evident in Glass patterns and the café wall illusion.

11. A Unified Explanation of Hyperacuity and Illusory Contour Data

Lesher's (1993) dissertation contains (among other projects) simulations describing how the BCS can fit the illusory contour data of Project 9 in a manner that unifies the treatment of hyperacuity data and illusory contour formation, as first described by Grossberg (1987). Tradeoffs in network design for optimal spatial resolution and for reconciling long-range contextual information with local data are thereby accorded a unified treatment.

12. Design of Working Memories for Temporary Storage and Learning of Event Sequences: Applications to 3-D Visual Object Recognition [Articles 1–4]

Working memory is the type of memory whereby a telephone number, or other novel temporally ordered sequence of events, can be temporarily stored and then performed (Baddeley, 1976). Working memory, a kind of short-term memory (STM), can be quickly erased by a distracting event, unlike long-term memory (LTM). There is a large experimental literature about working memory, as well as a variety of models (Atkinson and Shiffrin, 1971; Cohen and Grossberg, 1987; Cohen, Grossberg, and Stork, 1987; Elman, 1990; Grossberg, 1970, 1978a, 1978b; Grossberg and Pepe, 1971; Grossberg and Stone, 1986; Gutfreund and Mezard, 1988; Guyon, Personnaz, Nadal, and Dreyfus. 1988; Jordan, 1986: Reeves and Sperling, 1986; Schreter and Pfeifer, 1989; Seibert, 1991; Seibert and Waxman, 1990a, 1990b; Wang and Arbib, 1990).

The present class of models, called STORE (Sustained Temporal Order REcurrent) models, exhibit properties that have heretofore not been available in a dynamically defined working memory. In particular, STORE working memories are designed to encode the invariant temporal order of sequential events, or items, that may be presented with widely differing growth rates, amplitudes, durations, and interstimulus intervals. The STORE model is also designed to enable all possible groupings of the events stored in STM to be stabiy learned and remembered in LTM, even as new events perturb the system. In other words, these working memories enable chunks (also called compressed, categorical, or unitized representations) of a stored list to be encoded in LTM in a manner that is not erased by the continuous barrage of new inputs to the working memory.

Working memories with these properties are important in many applications wherein properties of behavioral self-organization are needed. Three important applications are real-time self-organization of codes for variable-rate speech perception, sensory-motor planning, and 3-D visual object recognition. Architectures for the first two types of application are described in Cohen, Grossberg and Stork (1987) and Grossberg and Kuperstein (1989). STORE working memory can both simplify and extend the capabilities of the Seibert and Waxman model for 3-D visual object recognition (Seibert and Waxman, 1990a, 1990b; Seibert, 1991).

The STORE neural network working memories are based upon algebraically characterized working memories that were introduced by Grossberg (1978a, 1978b). These algebraic working memories were designed to explain a variety of challenging psychological data concerning working memory storage and recall. In these models, individual events are stored in working memory in such a way that the pattern of STM activity across event representations encodes both the events that have occurred and the temporal order in which they have occurred. In the cognitive literature, such a working memory is often said to store both *item* information and *order* information (Healy, 1975; Lee and Estes, 1981; Ratcliff, 1978). The models also include a mechanism for reading out events in the stored temporal order. An event sequence can hereby be performed from STM even if it is not yet incorporated through learning into LTM, much as a new telephone number can be repeated the first time that it is heard.

The large data base on working memory shows that storage and performance of temporal order information from working memory is not always veridical (Atkinson and Shiffrin, 1971; Baddeley, 1978; Reeves and Sperling, 1986) These deviations from veridical temporal order in STM could be explained by the algebraic working memory model as consequences of two design principles that have clear adaptive value. These principles are called the Invariance Principle and the Normalization Rule (Grossberg, 1978b).

Invariance Principle: The spatial patterns of STM activation across the event representations of a working memory are stored and reset in response to sequentially presented events in such a way as to leave the temporal order codes of all past event groupings invariant.

In particular, a temporal list of events is encoded in STM in a way that preserves the stability of previously learned LTM codes for familiar sublists of the list. For example, suppose that the word MY has previously been stored in a working memory's STM and has established a learned chunk in LTM. Suppose that the word MYSELF is then stored for the first time in STM. The word MY is a syllable of MYSELF. The STM encoding of MY as a syllable of MYSELF may not be the same as its STM encoding as a word in its own right. On the other hand, MY's STM encoding as part of MYSELF should not be allowed to force forgetting of the LTM code for MY as a word in its own right. If it did, familiar words, such as MY, could not be learned as parts of larger words, such as MYSELF, without eliminating the smaller words from the lexicon. More generally, new wholes could not be built from familiar parts without erasing LTM of the parts.

Normalization Rule: The Normalization Rule algebraically instates the classical property of the limited capacity of STM (Atkinson and Shiffrin, 1971).

The present research has shown how to design real-time neural networks that are capable of storing in working memory the temporal order of arbitrary sequences of item representations. These events may occur with arbitrary rates, durations, and repeats. They are stored in such a way that a categorization network (for example an ARTMAP) can stably learn arbitrary subsequences of the stored events in compressed representations, or chunks.

This work opens up a new approach to solving the *subgoal planning problem.* This core problem of cognitive psychology and artificial intelligence acknowledges that the correct sequence of choices with which to attain a goal is often not known until choices are somehow made and the goal is attained. A STORE working memory enables such choices to be stored through time in such a way that subsequent success at a goal can select and learn those choice subsequences that led to success and use these preferred subsequences for future planning and control.

13. A Neural Architecture for Adaptive Control of Arm Movements [Articles 5–7,39–41,43]

This work has introduced and analysed several key neural modules for the adaptive control of human and animal arm movements, and, by extension, provides new types of autonomous controllers for technological applications. These modules include the Vector Integration to Endpoint (VITE) model for synchronous variable-speed control of multijoint arm trajectories, and the Factorization of Length and Tension (FLETE) model for accurate position control under unexpected and predictive changes in external forces. The VITE model is linked to neural data about parietal cortex, motor cortex, and basal ganglia. The FLETE model helps to explain data about spinal cord and cerebellum.

Further studies have shown how the correct VITE circuit parameters may be learned in an unsupervised way during real-time performance, and how opponent combinations of corollary discharge signals to the eyes may be organized to compute a cyclopean vergence-spherical coordinate system that represents the location of a foveated target in head-centered spatial coordinates.

14. What-and-Where Neural Networks for Object Localization and Recognition [Article 13]

This work describes a neural network model of how information about Where an object is can be used to help recognize What it is. The Where processing stream automatically computes an estimate of object location, size, and orientation. This spatial information is computed using the same types of neural mechanisms that are used in emergent visual segmentation by the Boundary Contour System (see Section 2). Thus spatial mechanisms may be viewed as a later instantiation of mechanisms that are used for visual perception at earlier processing stages.

The Where information is used to transform the What representation of an object into an invariant form whereby it can be autonomously recognized by an ART or ARTMAP system (see Section 1).

This What-and-Where network is inspired by cortical data about the parallel processing streams that pass through inferotemporal cortex and parietal cortex. These parallel streams are used to recognize objects (What) and to locate and manipulate them in space (Where).

15. Neural Pattern Generators for Quadruped Gait Generation [Articles 27–32]

This research has disclosed nonlinear neural network oscillators that are capable of generating the sequence of quadruped gaits—walk, trot, pace, and gallop—that is known from quadruped locomotion. Phase transitions from one gait pattern to another, including an increase in oscillation frequency, occur as a descending GO signal command is increased. These circuits are also competent to simulate the in-phase and anti-phase relationships of variable-frequency finger movements, the human walk-run gait transition, and the elephant amble-walk transition. The work hereby clarifies how a biologically important class of complex nonlinear neural oscillators work, while providing examples of new controllers for possible future robots that could walk or run over bumpy terrain.

16. References for Boston University Project Summaries

Aks, D.J. and Enns, J.T. (1992). Visual search for direction of shading is influenced by apparent depth. *Perception and Psychophysics*, **52**, 63–74.

Atkinson, R.C. and Shiffrin, R.M. (1971). The control of short term memory. *Scientific American*, August, 82–90.

Baddeley, A.D. (1976). **The psychology of memory**. New York: Basic Books.

Bravo M. and Blake R. (1990). Preattentive vision and perceptual groups. *Perception*, **19**, 515–522.

Chelazzi, L., Miller, E.K., Duncan, J., and Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature*, **363**, 345–347.

Cohen, M.A. and Grossberg, S. (1987). Masking fields: A massively parallel neural architecture of learning, recognizing, and predicting multiple groupings of patterned data. *Applied Optics*, **26**, 1866–1891.

Cohen, M.A., Grossberg, S., and Stork, D. (1987). Recent developments in a neural model of real-time speech analysis and synthesis. In M. Caudill and C. Butler (Eds.) **Proceedings of the IEEE international conference on neural networks**, San Diego, **IV**, 443–454.

Cohen, A. and Ivry, R.B. (1991). Density effects in conjunctive search: Evidence for a coarse location mechanism of feature integration. *Journal of Experimental Psychology: Human Perception and Performance*, **17**, 891–901.

Egeth, H., Virzi, R.A., and Garbart, H. (1984). Searching for conjunctively defined targets. *Journal of Experimental Psychology: Human Perception and Performance*, **10**, 32–39.

Elman, J.L. (1990). Finding structure in time. *Cognitive Science*, **14**, 179–211.

Enns, J.T. and Rensink, R.A. (1990). Influence of scene-based properties on visual search. *Science*, **247**, 721–723.

Gove, A. (1993). A neural network model of visual segmentation: Illusory contour formation, brightness induction, and grouping of scenic elements. PhD Thesis, Boston University.

Grossberg, S. (1970). Some networks that can learn, remember, and reproduce any number of complicated space-time patterns, II. *Studies in Applied Mathematics*, **49**, 135–166.

Grossberg, S. (1978a). Behavioral contrast in short-term memory: Serial binary memory models or parallel continuous memory models? *Journal of Mathematical Psychology*, **17**, 199–219.

Grossberg, S. (1978b). A theory of human memory: Self-organization and performance of sensory-motor codes, maps, and plans. In R. Rosen and F. Snell (Eds.), **Progress in theoretical biology**, pp. 233–374. New York: Academic Press. Reprinted in S. Grossberg (Ed.), **Studies of mind and brain.** Boston: Reidel Press, 1982.

Grossberg, S. (1987). Cortical dynamics of three-dimensional form, color, and brightness perception, Parts I and II. *Perception and Psychophysics*, **41**, 87–158.

Grossberg, S. and Kuperstein, M. (1989). **Neural dynamics of sensory-motor control: Expanded edition.** Elmsford, NY: Pergamon Press.

Grossberg, S. and Mingolla, E. (1985a). Neural dynamics of form perception: Boundary completion, illusory figures, and neon color spreading. *Psychological Review*, **92**, 173–211.

Grossberg, S. and Mingolla, E. (1985b). Neural dynamics of perceptual grouping: Textures, boundaries, and emergent segmentations. *Perception and Psychophysics*, **38**, 141–171.

Grossberg, S. and Mingolla, E. (1987). Neural dynamics of surface perception: Boundary webs, illuminants, and shape-from-shading. *Computer Vision, Graphics, and Image Processing*, **37**, 116–165.

Grossberg, S. and Pepe, J. (1971). Spiking threshold and overarousal effects in serial learning. *Journal of Statistical Physics*, **3**, 95–125.

Grossberg, S. and Stone, G.O. (1986). Neural dynamics of attention switching and temporal order information in short term memory. *Memory and Cognition*, **14**, 451–468.

Gutfreund, H. and Mezard, M. (1988). Processing of temporal sequences in neural networks. *Physiology Review Letters*, **61**, 235–238.

Guyon, I., Personnaz, L., Nadal, J.P. and Dreyfus, G. (1988). Storage retrieval of complex sequences in neural networks. *Physiology Review A*, **38**, 6365–6372.

He, Z.J. and Nakayama, K. (1992). Surface features in visual search. *Nature*, **359**, 231–233.

Healy, A.F. (1975). Separating item from order information in short-term memory. *Journal of Verbal Learning and Verbal Behavior*, **13**, 644–655.

Humphreys, G.W., Quinlan, P.T., and Riddoch, M.J. (1989). Grouping processes in visual search: Effects with single and combined feature targets. *Journal of Experimental Psychology: General*, **118**, 258–279.

Jordan, M.I. (1986). Serial order: A parallel distributed processing approach. Institute for Cognitive Science, Report 8604. University of California, San Diego.

Lee, C. and Estes, W.K. (1981). Item and order information in short-term memory: Evidence for multilevel perturbation processes. *Journal of Experimental Psychology: Human Learning and Memory*, **1**, 149–169.

Lesher, G.W. (1993). Neural networks for vision and pattern recognition: Boundary completion, spatial mapping, and multidimensional data fusion. PhD Thesis, Boston University. Ann Arbor: University Microfilms 9401999.

Mordkoff, J.T., Yantis, S., and Egeth H.E. (1990). Detecting conjunctions of color and form in parallel. *Perception and Psychophysics*, **5**, 157–168.

Nakayama, K. and Silverman, G.H. (1986). Serial and parallel processing of visual feature conjunctions. *Nature*, **320**, 264–265.

Nogueira, C.A.M. (1993). A neural network model of visual motion perception. PhD Thesis, Boston University.

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, **85**, 59–108.

Ratcliff, R. (1990). Connectionist models of recognition memory: Constraints imposed by learning and forgetting functions. *Psychological Review*, **97**, 285–308.

Reeves, A. and Sperling, G. (1986). Attention gating in short-term visual memory. *Psychological Review*, **93**, 180–206.

Schreter, Z. and Pfeifer, R. (1989). Short-term memory/long-term memory interactions in connectionist simulations of psychological experiments on list learning. In L. Personnaz and G. Dreyfus (Eds.), **Neural networks from models to applications.** Paris: I.D.S.E.T.

Seibert, M.C. (1991). Neural networks for machine vision: Learning three-dimensional object recognition. PhD Dissertation, Boston University.

Seibert, M.C. and Waxman, A.M. (1990a). Learning aspect graph representations from view sequences. In D.S. Touretzky (Ed.), **Advances in neural information processing systems 2.** San Mateo, CA: Morgan Kaufmann Publishing, pp. 258–265.

Seibert, M.C. and Waxman, A.M. (1990b). Learning aspect graph representations of 3D objects in a neural network. In M. Caudill (Ed.), **Proceedings of the international joint conference on neural networks**, Washington, DC, **2**, 233–236. Hillsdale, NJ: Erlbaum.

Treisman, A. and Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, **16**, 97–136.

Treisman, A. and Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception and Performance*, **16**, 459–478.

Wang, D. and Arbib, M.A. (1990). Complex temporal sequence learning based on short-term memory. *Proceedings of the IEEE*, **78**(9), 1536–1543.

Wolfe, J.M., Cave, K.R., and Franzel, S.L. (1989). Guided search: An alternative to the feature integration model of visual search. *Journal of Experimental Psychology: Human Perception and Performance*, **15**, 419–433.

Wolfe, J.M. and Friedman-Hill, S.R. (1992). Part-whole relationships in visual search. *Investigative Opthalmology and Visual Science*, **33**, 1355.

VI. SELECTED BOSTON UNIVERSITY ABSTRACTS

WORKING MEMORY NETWORKS FOR LEARNING TEMPORAL ORDER WITH APPLICATION TO 3-D VISUAL OBJECT RECOGNITION

Gary Bradski†, Gail A. Carpenter‡, and Stephen Grossberg§

Neural Computation, 1992, 4, 270–286

Abstract

Working memory neural networks, called Sustained Temporal Order REcurrent (STORE) models, encode the invariant temporal order of sequential events in short-term memory (STM). Inputs to the networks may be presented with widely differing growth rates, amplitudes, durations, and interstimulus intervals without altering the stored STM representation. The STORE temporal order code is designed to enable groupings of the stored events to be stably learned and remembered in real time, even as new events perturb the system. Such invariance and stability properties are needed in neural architectures which self-organize learned codes for variable-rate speech perception, sensory-motor planning, or 3-D visual object recognition. Using such a working memory, a self-organizing architecture for invariant 3-D visual object recognition is described. The new model is based on the model of Seibert and Waxman (1990a), which builds a 3-D representation of an object from a temporally ordered sequence of its 2-D aspect graphs. The new model, called an ARTSTORE model, consists of the following cascade of processing modules: Invariant Preprocessor → ART 2 → STORE Model → ART 2 → Outstar Network.

† Supported by DARPA (AFOSR 90-0083).

‡ Supported in part by British Petroleum (89-A-1204), DARPA (AFOSR 90-0083) and the National Science Foundation (NSF IRI 90-00530).

§ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-128 and AFOSR 90-0175), DARPA (AFOSR 90-0083), and the National Science Foundation (NSF IRI 90-24877).

STORE WORKING MEMORY NETWORKS FOR STORAGE AND RECALL OF ARBITRARY TEMPORAL SEQUENCES

Gary Bradski†, Gail A. Carpenter‡, and Stephen Grossberg§

Technical Report CAS/CNS-TR-92-028, Boston University
Submitted to *Biological Cybernetics*

Abstract

Neural network models of working memory, called Sustained Temporal Order REcurrent (STORE) models, are described. They encode the invariant temporal order of sequential events in short term memory (STM) in a way that mimics cognitive data about working memory, including primacy, recency, and bowed order and error gradients. As new items are presented, the pattern of previously stored items is invariant in the sense that relative activations remain constant through time. This invariant temporal order code enables all possible groupings of sequential events to be stably learned and remembered in real time, even as new events perturb the system. Such a competence is needed to design self-organizing temporal recognition and planning systems in which any subsequence of events may need to be categorized in order to control and predict future behavior or external events. STORE models show how arbitrary event sequences may be invariantly stored, including repeated events. A preprocessor interacts with the working memory to represent event repeats in spatially separate locations. It is shown why at least two processing levels are needed to invariantly store events presented with arbitrary durations and interstimulus intervals. It is also shown how network parameters control the type and shape of primacy, recency, or bowed temporal order gradients that will be stored.

† Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0128) and the Office of Naval Research (ONR N00014-91-J-4100 and ONR N00014-92-J-1309).

‡ Supported in part by British Petroleum (BP 89A-1204), ARPA (AFOSR 90-0083 and ONR N00014-92-J-4015), the National Science Foundation (NSF IRI-90-00530), and the Office of Naval Research (ONR N00014-91-J-4100).

§ Supported in part by the Air Force Office of Scientific Research (AFOSR F49620-92-J-0225), ARPA (AFOSR 90-0083 and ONR N00014-92-J-4015) and the Office of Naval Research (ONR N00014-91-J-4100 and ONR N00014-92-J-1309).

NORMAL AND AMNESIC LEARNING, RECOGNITION, AND MEMORY BY A NEURAL MODEL OF CORTICO-HIPPOCAMPAL INTERACTIONS

Gail A. Carpenter and Stephen Grossberg

Technical Report CAS/CNS TR-92-021, Boston University
Trends in Neurosciences, 1993, **16**, 131–137

Abstract

The processes by which humans and other primates learn to recognize objects have been the subject of many models. Processes such as learning, categorization, attention, memory search, expectation, and novelty detection work together at different stages to realize object recognition. In this article, Gail Carpenter and Stephen Grossberg describe one such model class (Adaptive Resonance Theory, ART) and discuss how its structure and function might relate to known neurological learning and memory processes, such as how inferotemporal cortex can recognize both specialized and abstract information, and how medial temporal amnesia may be caused by lesions in the hippocampal formation. The model also suggests how hippocampal and inferotemporal processing may be linked during recognition learning.

Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175), British Petroleum (BP 89A-1204), DARPA (AFOSR 90-0083), the National Science Foundation (NSF IRI-90-00530), and the Office of Naval Research (ONR N00014-91-J-4100).

A WHAT-AND-WHERE NEURAL NETWORK FOR INVARIANT IMAGE PREPROCESSING

Gail A. Carpenter†, Stephen Grossberg‡, and Gregory W. Lesher§

Proceedings of the International Joint Conference on Neural Networks, 1992, **III**, 303–308

Abstract

A feedforward neural network for invariant image preprocessing is proposed that represents the position, orientation, and size of an image figure (where it is) in a multiplexed spatial map. This map is used to generate an invariant representation of the figure that is insensitive to position, orientation, and size for purposes of pattern recognition (what it is). A multiscale array of oriented filters, followed by competition between orientations and scales is used to define the Where filter.

† Supported in part by British Petroleum (BP 89-A-1204), DARPA (AFOSR 90-0083), the National Science Foundation (NSF IRI-90-00530), and the Office of Naval Research (ONR N00014-91-J-4100).

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175), DARPA (AFOSR 90-0083), and the Office of Naval Research (ONR N00014-91-J-4100).

§ Supported under a National Science Foundation Graduate Fellowship.

FUZZY ARTMAP: A NEURAL NETWORK ARCHITECTURE FOR INCREMENTAL SUPERVISED LEARNING OF ANALOG MULTIDIMENSIONAL MAPS

Gail A. Carpenter†, Stephen Grossberg‡, Natalya Markuzon§, John H. Reynolds¶, and David B. Rosen¶

IEEE Transactions on Neural Networks, 1992, **3**, 698–713

Abstract

A new neural network architecture is introduced for incremental supervised learning of recognition categories and multidimensional maps in response to arbitrary sequences of analog or binary input vectors, which may represent fuzzy or crisp sets of features. The architecture, called Fuzzy ARTMAP, achieves a synthesis of fuzzy logic and Adaptive Resonance Theory (ART) neural networks by exploiting a close formal similarity between the computations of fuzzy subsethood and ART category choice, resonance, and learning. Fuzzy ARTMAP also realizes a new Minimax Learning Rule that conjointly minimizes predictive error and maximizes code compression, or generalization. This is achieved by a match tracking process that increases the ART vigilance parameter by the minimum amount needed to correct a predictive error. As a result, the system automatically learns a minimal number of recognition categories, or "hidden units", to meet accuracy criteria. Category proliferation is prevented by normalizing input vectors at a preprocessing stage. A normalization procedure called complement coding leads to a symmetric theory in which the AND operator ($\wedge$) and the OR operator ($\vee$) of fuzzy logic play complementary roles. Complement coding uses on-cells and off-cells to represent the input pattern, and preserves individual feature amplitudes while normalizing the total on-cell/off-cell vector. Learning is stable because all adaptive weights can only decrease in time. Decreasing weights correspond to increasing sizes of category "boxes". Smaller vigilance values lead to larger category boxes. Improved prediction is achieved by training the system several times using different orderings of the input set. This voting strategy can also be used to assign confidence estimates to competing predictions given small, noisy, or incomplete training sets. Four classes of simulations illustrate Fuzzy ARTMAP performance as compared to benchmark back propagation and genetic algorithm systems. These simulations include (i) finding points inside vs. outside a circle; (ii) learning to tell two spirals apart; (iii) incremental approximation of a piecewise continuous function; and (iv) a letter recognition database. The Fuzzy ARTMAP system is also compared to Salzberg's NGE system and to Simpson's FMMC system.

† Supported in part by British Petroleum (89-A-1204), DARPA (AFOSR 90-0083), the National Science Foundation (NSF IRI 90-00530) and the Office of Naval Research (ONR N00014-91-J-4100).

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175), DARPA (AFOSR 90-0083) and the Office of Naval Research (ONR N00014-91-J-4100).

§ Supported in part by British Petroleum (89-A-1204) and the National Science Foundation (NSF IRI 90-00530).

¶ Supported in part by DARPA (AFOSR 90-0083).

NEURAL CONTROL OF INTERLIMB COORDINATION AND GAIT TIMING IN BIPEDS AND QUADRUPEDS

Michael A. Cohen†, Stephen Grossberg‡, and Christopher Pribe§

Technical Report CAS/CNS-TR-93-004, Boston University
Submitted to *Journal of Neurophysiology*

Abstract

1) A family of central pattern generators, called GO Gait Generators, is described in which both the frequency and the relative phase of oscillations are controlled by a scalar arousal or GO signal that instantiates the will to act. The model cells obey shunting membrane equations, and interact via fast excitatory feedback signals and slow inhibitory feedback signals, organized as an on-center off-surround anatomy.

2) With two excitatory cells, or cell populations, the model describes an opponent processing network in which both in-phase and anti-phase oscillations can occur at different arousal levels. This two-channel oscillator can also produce phase transitions from either in-phase to anti-phase oscillations, or anti-phase to in-phase oscillations, in different parameter ranges, as the GO signal increases.

3) The two-channel oscillator is used to simulate data from human bimanual finger coordination tasks in which anti-phase oscillations at low frequencies spontaneously switch to in-phase oscillations at high frequencies, in-phase oscillations can be performed both at low and high frequencies, phase fluctuations occur at the anti-phase in-phase transition, and a "seagull effect" of larger errors occurs at intermediate phases. When driven by environmental patterns with intermediate phase relationships, the model's output exhibits a tendency to slip toward purely in-phase and anti-phase relationships as observed in humans subjects.

4) A four-channel oscillator is used to simulate quadruped vertebrate gaits, including the amble, the walk, all three pairwise gaits (trot, pace, and gallop), and the pronk. Spatial or temporal asymmetries in oscillator activation by the GO signal can trigger these transitions. Rapid transitions are simulated in the order—walk, trot, pace, and gallop—that occurs in the cat.

5) This precise switching control is achieved by using GO-dependent modulation of the model's inhibitory interactions that generates a different functional connectivity in a single network at different arousal levels. Such task-specific modulation of functional connectivity in neural pattern generators has been experimentally reported in invertebrates. A role for such a mechanism in gait-switching is predicted to occur in vertebrates.

6) A four channel oscillator can generate the two standard human gaits: the walk and the run. Although these two gaits are qualitatively different, they both have the same limb order and may exhibit oscillation frequencies that overlap. The model simulates the walk and the run via qualitatively different waveform shapes. The fraction of cycle that activity is above threshold quantitatively distinguishes the two gaits, much as the duty cycles of the feet are longer in the walk than in the run.

† Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0128 and AFOSR F49620-92-J-0225).

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175 and AFOSR F49620-92-J-0225), the National Science Foundation (NSF IRI-90-24877), and the Office of Naval Research (ONR N00014-92-J-1309).

§ Supported in part by the Army Research Office (ARO DAAL03-88-K-0088), the Advanced Research Projects Agency (AFOSR 90-0083), the National Science Foundation (NSF IRI-90-24877), and the Office of Naval Research (ONR N00014-92-J-1309).

FUZZY ART: FAST STABLE LEARNING AND CATEGORIZATION OF ANALOG PATTERNS BY AN ADAPTIVE RESONANCE SYSTEM

Gail A. Carpenter†, Stephen Grossberg‡, and David B. Rosen*

Neural Networks, 1991, 4, 759–771

Abstract

A Fuzzy Adaptive Resonance Theory (ART) model capable of rapid stable learning of recognition categories in response to arbitrary sequences of analog or binary input patterns is described. Fuzzy ART incorporates computations from fuzzy set theory into the ART 1 neural network, which learns to categorize only binary input patterns. The generalization to learning both analog and binary input patterns is achieved by replacing appearances of the intersection operator ($\cap$) in ART 1 by the MIN operator ($\wedge$) of fuzzy set theory. The MIN operator reduces to the intersection operator in the binary case. Category proliferation is prevented by normalizing input vectors at a preprocessing stage. A normalization procedure called complement coding leads to a symmetric theory in which the MIN operator ($\wedge$) and the MAX operator ($\vee$) of fuzzy set theory play complementary roles. Complement coding uses on-cells and off-cells to represent the input pattern, and preserves individual feature amplitudes while normalizing the total on-cell/off-cell vector. Learning is stable because all adaptive weights can only decrease in time. Decreasing weights correspond to increasing sizes of category "boxes". Smaller vigilance values lead to larger category boxes. Learning stops when the input space is covered by boxes. With fast learning and a finite input set of arbitrary size and composition, learning stabilizes after just one presentation of each input pattern. A fast-commit slow-recode option combines fast learning with a forgetting rule that buffers system memory against noise. Using this option, rare events can be rapidly learned, yet previously learned memories are not rapidly erased in response to statistically unreliable input fluctuations.

† Supported in part by British Petroleum (89-A-1204), DARPA (AFOSR 90-0083), and the National Science Foundation (NSF IRI-90-00530).

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175) and DARPA (AFOSR 90-0083).

* Supported in part by DARPA (AFOSR 90-0083).

CORTICAL DYNAMICS OF FEATURE BINDING AND RESET: CONTROL OF VISUAL PERSISTENCE

Gregory Francis†, Stephen Grossberg‡, and Ennio Mingolla§

Vision Research, in press, 1994

Abstract

We hypothesize that many properties of visual persistence are caused by positive feedback in the visual cortical circuits that are responsible for the binding or segmentation of visual features into coherent visual forms, and that the degree of persistence is limited by circuits that reset these segmentations at stimulus offset. We propose a model of the cortical local circuitry responsible for such feature binding and reset, and use the model to quantitatively simulate psychophysical data showing increase of persistence with spatial separation of a masking stimulus; inverse relation of persistence to flash luminance and duration; greater persistence of illusory contours than real contours, with maximal persistence at an intermediate stimulus duration; and dependence of persistence on pre-adapted stimulus orientation. Data concerning cortical cell responses to illusory and real contours are also analysed, as are alternative models of feature binding and persistence properties.

† Supported by a National Science Foundation Graduate Fellowship.

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175), DARPA (AFOSR 90-0083), and the Office of Naval Research (ONR N00014-91-J-4100).

§ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175).

NEURAL REPRESENTATIONS FOR SENSORY-MOTOR CONTROL, I: HEAD-CENTERED 3-D TARGET POSITIONS FROM OPPONENT EYE COMMANDS

Douglas Greve†, Stephen Grossberg‡, Frank Guenther†, and Daniel Bullock†

Acta Psychologica, 1992, **82**, 115–138

Abstract

This article describes how corollary discharges from outflow eye movement commands can be transformed by two stages of opponent neural processing into a head-centered representation of 3-D target position. This representation implicitly defines a cyclopean coordinate system whose variables approximate the binocular vergence and spherical horizontal and vertical angles with respect to the observer's head. Various psychophysical data concerning binocular distance perception and reaching behavior are clarified by this representation. The representation provides a foundation for learning head-centered and body-centered invariant representations of both foveated and non-foveated 3-D target positions. It also enables a solution to be developed of the classical motor equivalence problem, whereby many different joint configurations of a redundant manipulator can all be used to realize a desired trajectory in 3-D space.

‡ Supported in part Air Force Office of Scientific Research (AFOSR URI 90-0175), Defense Advanced Research Projects Agency (DARPA AFOSR-90-0083), and the National Science Foundation (NSF IRI-87-16960 and NSF IRI-90-24877).

† Supported in part by the National Science Foundation (NSF IRI-87-16960 and NSF IRI-90-24877).

ADAPTIVE VECTOR INTEGRATION TO ENDPOINT: SELF-ORGANIZING NEURAL CIRCUITS FOR CONTROL OF PLANNED MOVEMENT TRAJECTORIES

Paolo Gaudiano† and Stephen Grossberg‡

Human Movement Science, 1992, **11**, 141–155

Abstract

A neural network model is described for adaptive control of arm movement trajectories during visually guided reaching. The model clarifies how a child, or infant robot, can learn to reach for objects that it sees. Piaget has provided basic insights with his concept of a *circular reaction*. As an infant makes internally generated hand movements, the eyes automatically follow this motion. A transformation is learned between the visual representation of hand position and the motor representation of hand position. Learning of this transformation eventually enables the child to accurately reach for visually detected targets. Grossberg and Kuperstein (1989) have shown how the eye movement system can use visual error signals to correct movement parameters via cerebellar learning. Here it is shown how the arm movement system can endogenously generate movements which lead to adaptive tuning of arm control parameters. These movements also activate the target position representations that are used to learn the visuo-motor transformation that controls visually guided reaching. The arm movement properties obtain in the Adaptive Vector Integration to Endpoint (AVITE) model, an adaptive neural circuit based on the VITE model for arm and speech trajectory generation of Bullock and Grossberg (1988a).

† Supported in part by the National Science Foundation (NSF IRI-87-16960)

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175), DARPA (AFOSR 90-0083), and the National Science Foundation (NSF IRI-87-16960).

A SOLUTION OF THE FIGURE-GROUND PROBLEM FOR BIOLOGICAL VISION

Stephen Grossberg†

Technical Report CAS/CNS-TR-92-020, Boston University
Neural Networks, 1993, 6, 463–483

Abstract

A neural network model of 3-D visual perception and figure-ground separation by visual cortex is introduced. The theory provides a unified explanation of how a 2-D image may generate a 3-D percept; how figures pop-out from cluttered backgrounds; how spatially sparse disparity cues can generate continuous surface representations at different perceived depths; how representations of occluded regions can be completed and recognized without usually being seen; how occluded regions can sometimes be seen during percepts of transparency; how high spatial frequency parts of an image may appear closer than low spatial frequency parts; how sharp targets are detected better against a figure and blurred targets are detector better against a background; how low spatial frequency parts of an image may be fused while high spatial frequency parts are rivalrous; how sparse blue cones can generate vivid blue surface percepts; how 3-D neon color spreading, visual phantoms, and tissue contrast percepts are generated; how conjunctions of color-and-depth may rapidly pop-out during visual search. These explanations arise derived from an ecological analysis of how monocularly viewed parts of an image inherit the appropriate depth from contiguous binocularly viewed parts, as during DaVinci stereopsis. The model predicts the functional role and ordering of multiple interactions within and between the two parvocellular processing streams that join LGN to prestriate area V4. Interactions from cells representing larger scales and disparities to cells representing smaller scales and disparities are of particular importance.

† Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175), ARPA (AFOSR 90-0083 and ONR N00014-92-J-4015), and the Office of Naval Research (ONR N00014-91-J-4100).

3-D VISION AND FIGURE-GROUND SEPARATION BY VISUAL CORTEX

Stephen Grossberg†

Technical Report CAS/CNS-TR-92-019, Boston University
Perception and Psychophysics, 1994, **55**, 48–120

Abstract

A neural network theory of 3-D vision, called FACADE Theory, is described. The theory proposes a solution of the classical figure-ground problem for biological vision. It does so by suggesting how boundary representations and surface representations are formed within a Boundary Contour System (BCS) and a Feature Contour System (FCS). The BCS and FCS interact reciprocally to form 3-D boundary and surface representations that are mutually consistent. Their interactions generate 3-D percepts wherein occluding and occluded object parts are separated, completed, and grouped. The theory clarifies how preattentive processes of 3-D perception and figure-ground separation interact reciprocally with attentive processes of spatial localization, object recognition, and visual search. A new theory of stereopsis is proposed that predicts how cells sensitive to multiple spatial frequencies, disparities, and orientations are combined by context-sensitive filtering, competition, and cooperation to form coherent BCS boundary segmentations. Several factors contribute to figure-ground pop-out, including: boundary contrast between spatially contiguous boundaries, whether due to scenic differences in luminance, color, spatial frequency, or disparity; partially ordered interactions from larger spatial scales and disparities to smaller scales and disparities; and surface filling-in restricted to regions surrounded by a connected boundary. Phenomena such as 3-D pop-out from a 2-D picture, DaVinci stereopsis, 3-D neon color spreading, completion of partially occluded objects, and figure-ground reversals are analysed. The BCS and FCS subsystems model aspects of how the two parvocellular cortical processing streams that join the Lateral Geniculate Nucleus to prestriate cortical area V4 interact to generate a multiplexed representation of Form-And-Color-And-DEpth, or FACADE, within area V4. Area V4 is suggested to support figure-ground separation and to interact with cortical mechanisms of spatial attention, attentive object learning, and visual search. Adaptive Resonance Theory (ART) mechanisms model aspects of how prestriate visual cortex interacts reciprocally with a visual object recognition system in inferotemporal cortex (IT) for purposes of attentive object learning and categorization. Object attention mechanisms of the What cortical processing stream through IT cortex are distinguished from spatial attention mechanisms of the Where cortical processing stream through parietal cortex. Parvocellular BCS and FCS signals interact with the model What steam. Parvocellular FCS and magnocellular Motion BCS signals interact with the model Where stream. Reciprocal interactions between these visual, What, and Where mechanisms are used to discuss data about visual search and saccadic eye movements, including fast search of conjunctive targets, search of 3-D surfaces, selective search of like-colored targets, attentive tracking of multi-element groupings, and recursive search of simultaneously presented targets.

† Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175 and AFOSR F49620-92-J-0499), ARPA (AFOSR 90-0083 and ONR N00014-92-J-4015), and the Office of Naval Research (ONR N00014-91-J-4100).

NEURAL DYNAMICS OF MOTION PERCEPTION: DIRECTION FIELDS, APERTURES, AND RESONANT GROUPING

Stephen Grossberg† and Ennio Mingolla‡

Perception and Psychophysics, 1993, **53**, 243–278

Abstract

A neural network model of global motion segmentation by visual cortex is described. Called the Motion Boundary Contour System (BCS), the model clarifies how ambiguous local movements on a complex moving shape are actively reorganized into a coherent global motion signal. Unlike many previous researchers, we analyse how a coherent motion signal is imparted to all regions of a moving figure, not only to regions at which unambiguous motion signals exist. The model hereby suggests a solution to the global aperture problem. The Motion BCS describes how preprocessing of motion signals by a Motion Oriented Contrast Filter (MOC Filter) is joined to long-range cooperative grouping mechanisms in a Motion Cooperative-Competitive Loop (MOCC Loop) to control phenomena such as motion capture. The Motion BCS is computed in parallel with the Static BCS of Grossberg and Mingolla (1985a, 1985b, 1987). Homologous properties of the Motion BCS and the Static BCS, specialized to process movement directions and static orientations, respectively, support a unified explanation of many data about static form perception and motion form perception that have heretofore been unexplained or treated separately. Predictions about microscopic computational differences of the parallel cortical streams $V1 \rightarrow MT$ and $V1 \rightarrow V2 \rightarrow MT$ are made, notably the magnocellular thick stripe and parvocellular interstripe streams. It is shown how the Motion BCS can compute motion directions that may be synthesized from multiple orientations with opposite directions-of-contrast. Interactions of model simple cells, complex cells, hypercomplex cells, and bipole cells are described, with special emphasis given to new functional roles in direction disambiguation for endstopping at multiple processing stages and to the dynamic interplay of spatially short-range and long-range interactions.

† Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175), DARPA (AFOSR 90-0083), and the Office of Naval Research (ONR N00014-91-J-4100).

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175).

A NEURAL THEORY OF ATTENTIVE VISUAL SEARCH: INTERACTIONS OF BOUNDARY, SURFACE, SPATIAL, AND OBJECT REPRESENTATIONS

Stephen Grossberg†, Ennio Mingolla‡ and William D. Ross§

Technical Report CAS/CNS-TR-93-038, Boston University
Psychological Review, in press, 1994

Abstract

Visual search data are given a unified quantitative explanation by a model of how spatial maps in the parietal cortex and object recognition categories in the inferotemporal cortex deploy attentional resources as they reciprocally interact with visual representations in the prestriate cortex. The model visual representations are organized into multiple boundary and surface representations. Visual search in the model is initiated by organizing multiple items that lie within a given boundary or surface representation into a candidate search grouping. These items are compared with object recognition categories to test for matches or mismatches. Mismatches can trigger deeper searches and recursive selection of new groupings until a target object is identified. This search model is algorithmically specified to quantitatively simulate search data using a single set of parameters, as well as to qualitatively explain a still larger data base, including data of Aks and Enns (1992), Bravo and Blake (1990), Chellazzi, Miller, Duncan, and Desimone (1993), Egeth, Virzi, and Garbart (1984), Cohen and Ivry (1991), Enns and Rensink (1990), He and Nakayama (1992), Humphreys, Quinlan, and Riddoch (1989), Mordkoff, Yantis, and Egeth (1990), Nakayama and Silverman (1986), Treisman and Gelade (1980), Treisman and Sato (1990), Wolfe, Cave, and Franzel (1989), and Wolfe and Friedman-Hill (1992). The model hereby provides an alternative to recent variations on the Feature Integration and Guided Search models, and grounds the analysis of visual search in neural models of preattentive vision, attentive object learning and categorization, and attentive spatial localization and orientation.

† Supported in part by Air Force Office of Scientific Research (AFOSR F49620-92-J-0499), ARPA (AFOSR 90-0083 and ONR N00014-92-J-4015), and the Office of Naval Research (ONR N00014-91-J-4100).

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175 and F49620-92-J-0334), the Northeast Consortium for Engineering Education (NCEE A303-21-93), and the Office of Naval Research (ONR N00014-91-J-4100).

§ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175), British Petroleum (BP 89A-1204), the National Science Foundation (NSF IRI 90-00530), and the Office of Naval Research (ONR N00014-91-J-4100).

THE ROLE OF EDGES AND LINE-ENDS IN ILLUSORY CONTOUR FORMATION

Gregory W. Lesher† and Ennio Mingolla‡

Vision Research, 1993, **33**, 2253–2270

Abstract

Illusory contours can be induced along directions approximately collinear to edges or approximately perpendicular to the ends of lines. Using a rating scale procedure, they explored the relation between the two types of inducers by systematically varying the thickness of inducing elements to result in varying amounts of "edge-like" or "line-like" induction. Inducers for the illusory figures consisted of concentric rings with arcs missing. Observers judged the clarity and brightness of illusory figures as the number of arcs, their thicknesses, and spacing were parametrically varied. Degree of clarity and amount of induced brightness were both found to be inverted-U functions of the number of arcs. These results mandate that any valid model of illusory contour formation must account for interference effects between parallel lines or between those neural units responsible for completion of boundary signals in directions perpendicular to the ends of thin lines. Line width was found to have an effect on both clarity and brightness, a finding inconsistent with those models which employ *only* completion perpendicular to inducer orientation.

† Supported in part by the Air Force Office of Scientific Research (AFOSR F49620-92-J-0334) and a National Science Foundation Graduate Fellowship.

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175 and AFOSR F49620-92-J-0334) and the Office of Naval Research (ONR N00014-91-J-4100).

THE PERCEPTION OF GLOBALLY COHERENT MOTION

Ennio Mingolla†, James T. Todd, and J. Farley Norman

Vision Research, 1992, **32**, 1015–1031

Abstract

How do human observers perceive a coherent pattern of motion from a disparate set of local motion measures? Our research has examined how ambiguous motion signals along straight contours are spatially integrated to obtain a globally coherent perception of motion. Observers viewed displays containing a large number of apertures, with each aperture containing one or more contours whose orientations and velocities could be independently specified. The total pattern of the contour trajectories across the individual apertures was manipulated to produce globally coherent motions, such as rotations, expansions, or translations. For displays containing only straight contours extending to the circumferences of the apertures, observers' reports of global motion direction were biased whenever the sampling of contour orientations was asymmetric relative to the direction of motion. Performance was improved by the presence of identifiable features, such as line ends or crossings, whose trajectories could be tracked over time. The reports of our observers were consistent with a pooling process involving a vector average of measures of the component of velocity normal to contour orientation, rather than with the predictions of the intersection-of-constraints analysis in velocity space.

† Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175).

VII. TECHNOLOGY TRANSFERS

Neural network systems, developed at Boston University with ARPA support, are being applied to areas that range from government and commercial to medical and even musical. Some examples of a rapidly growing number of technology transfers are listed below. Other examples are classified or proprietary. Many of these applications have been facilitated by collaborations of scientists and engineers from government laboratories and private industry with Boston University faculty and students. Technology transfer is accelerating, as MA and PhD graduates of the Department of Cognitive and Neural Systems move into full-time research and development positions in government, industry, and academia.

1. ART 1 is the central component of an airplane parts design and retrieval system at the Boeing Seattle plant. There, the system has been implemented in the Boeing 777 CAD system, where the neural architecture reduced parts inventory by a factor of 9 in the sections where it was used. System expansion is now planned. In addition, the parts retrieval system is implemented in the Boeing 747 and 767 production processes.

   Caudell, T., Smith, S., Johnson, C., Wunsch, D., and Escobedo, R. (1991). An industrial application of neural networks to reusable design. **Adaptive neural systems**, Technical Report BCS-CS-ACS-91-001, Seattle, WA: The Boeing Company, pp. 185–190.

   Smith, S.D.G., Escobedo, R., and Caudell, T.P. (1993). An industrial strength neural network application. **Proceedings of the world congress on neural networks (WCNN-93)**, Hillsdale, NJ: Lawrence Erlbaum Associates, **I**-490–494.

2. Applications of ART systems for manufacturing is the subject of a forthcoming book.

   Kumara, S.R.T., Merchawi, N.S., Karmarthi, S.V., and Thazhuthaveetil, M. (1993). **Neural networks in design and manufacturing.** Chapman and Hall Publishers.

3. Fuzzy ART is a key component of a robot sensory-motor system under development at MIT Lincoln Laboratory.

   Bachelder, I.A., Waxman, A.M., and Seibert, M. (1993). A neural system for mobile robot visual place learning and recognition. **Proceedings of the world congress on neural networks (WCNN-93)**, Hillsdale, NJ: Lawrence Erlbaum Associates, **I**-512–517.

4. ART 2-A is the basis of the commercial software program Open Sesame that allows a Macintosh operating system to adapt to a user's work habits.

   Johnson, C. (1993). Agent learns user's behavior. *Electrical Engineering Times*, June 28, pp. 43, 46.

   Alper Caglayan, President, Charles River Analytics, Inc., Cambridge, Massachusetts.

5. ART 2 and ART 2-A are being used at MIT Lincoln Laboratory for face recognition and 3-D object recognition.

   Seibert, M. and Waxman, A.M. (1991). Learning and recognizing 3D objects from multiple views in a neural system. In H. Wechsler (Ed.), **Neural networks for perception, Volume 1.** New York: Academic Press.

   Seibert, M. and Waxman, A.M. (1993). An approach to face recognition using saliency maps and caricatures. **Proceedings of the world congress on neural networks (WCNN-93)**, Hillsdale, NJ: Lawrence Erlbaum Associates, **III**-661–664.

Seibert, M. and Waxman, A.M. (1992). Adaptive 3D object recognition from multiple views. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **14**, 107–124.

6. ART 2 and ART 2A are being used at Sandia National Laboratories, for target recognition.

   Moya, M.M., Koch, M.W., and Hostetler, L.D. (1993). One-class classifier networks for target recognition applications. **Proceedings of the world congress on neural networks (WCNN-93)**, Hilisdale, NJ: Lawrence Erlbaum Associates, **III**-797–801.

7. ART 2 and ART 2-A are being used in Japan, for wave recognition in electrocardiograms.

   Suzuki. Y., Abe, Y., and Ono, K. (1993) Self-organizing QRS wave recognition system in ECG using ART 2. **Proceedings of the world congress on neural networks (WCNN-93)**, Hillsdale, NJ: Lawrence Erlbaum Associates, **IV**-39–42.

8. Although recently introduced, fuzzy ARTMAP is already being applied to a variety of problems. Some of these applications have been described in the public domain. These include control of nuclear reactors.

   Keyvan, S., Durg, A., and Rabelo, L.C. (1993). Application of artificial neural networks for development of diagnostic monitoring system in nuclear plants. *American Nuclear Society Conference Proceedings*, April 18–21, 1993.

9. ARTMAP is also being used for medical database analysis.

   Ham, F.M. and Han, S.W. (1993). Quantitative study of the QRS complex using fuzzy ARTMAP and the MIT/BIH arrhythmia database. **Proceedings of the world congress on neural networks (WCNN-93)**, Hillsdale, NJ: Lawrence Erlbaum Associates, **I**-207–211.

   Harvey, R.M. (1993). Nursing diagnosis by computers: An application of neural networks. *Nursing Diagnosis*, **4**, 26–34.

   Goodman, P.H., Kaburlasos, V.G., Egbert, D.D., Carpenter, G.A., Grossberg, S., Reynolds, J.H., Rosen, D.B., and Hartz, A.J. (1992). Fuzzy ARTMAP neural network compared to linear discriminant analysis prediction of the length of hospital stay in patients with pneumonia. **Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics** (Chicago, October, 1992). New York: IEEE Press, **I**, 748–753.

10. Another ARTMAP application is the prediction of protein secondary structure.

    Mehta, B.V., Vij, L., and Rabelo, L.C. (1993). Prediction of secondary structures of proteins using fuzzy ARTMAP. **Proceedings of the world congress on neural networks (WCNN-93)**, Hillsdale, NJ: Lawrence Erlbaum Associates, **I**-228–232.

11. The Sharp Corporation is developing commercial applications of ART and ARTMAP systems (K. Iizuka, Nara, Japan).

12. An enhanced BCS/FCS system is being used to process synthetic aperture radar (SAR) imagery. This system was developed at Boston University, using unclassified samples of SAR images. The technology was then transferred to MIT Lincoln Laboratory, where the system is being applied to a more complete SAR database.

    Allen Waxman, MIT Lincoln Laboratory.

13. The BCS/FCS system has been developed into a system for the automatic segmentation and labelling of medical magnetic resonance imagery, at Massachusetts General Hospital.

    Worth, A.J., Lehar, S., and Kennedy, D.N. (1992). A recurrent cooperative/competitive field for segmentation of magnetic resonance brain images. *IEEE Transactions on Knowledge and Data Engineering*, 4. 156-161.

    Dr. David Kennedy, Center for Morphometric Analysis, Massachusetts General Hospital.

14. A research team at the University of Hamburg (Germany) is also using the BCS/FCS for enhancement of MRI imagery.

    Heiko Neumann, Department of Informatics.

15. Mitre Corporation has applied the BCS/FCS system to detect and enhance coherent patterns in satellite weather imagery.

    Ira Smotroff, Senior Scientist, Mitre Corporation, Bedford, Massachusetts.

16. A system that uses the BCS/FCS for textural segmentation and classification of radar imagery is being developed at the Naval Surface Warfare Center.

    George W. Rogers, Dahlgren, Virginia.

17. BCS/FCS image processing has been used at Sandia National Laboratories in a system that produces a clean circuit board image, eliminating soldering residue and illumination distortions.

    Koch, M.W. and Moya, M.M. (1993). Detecting residue on a printed circuit board: An application of the Boundary Contour/Feature Contour System. **Proceedings of the World Congress on Neural Networks**, 1993, **III**, 789-792.

18. HNC is applying BCS/FCS as part of a government contract to improve cruise missile guidance and target segmentation.

    Robert Hecht-Nielsen, HNC, San Diego, California.

VIII. NORTHEASTERN UNIVERSITY PROJECT SUMMARIES

Adam Reeves
Department of Psychology
Northeastern University
Boston Massachusetts 02115

The proposed work concerned the mechanisms underlying perception of color. Work was proposed in three areas; color appearance in Mondriaan displays (I); adaptational history (II); and transient tritanopia/euchromatopsia (III). As reported last year, additional work has been done in electrophysiology, specifically concerning color in the ERG (IV), and spatial effects on the ERG and VEP (V).

1. Mondrian Displays

We have studied color constancy in Land-type "Mondrian" displays; that is, displays of several abutted homogeneous colored "papers", which in our work have been simulated on a high-resolution color monitor. This work has been done with L. E. Arend of the Eye Research Institute, as part of the URI grant.

As is now well known, we require observers to make matches between standard and comparison displays lit (in the simulation) by different phases of daylight. We ask whether color constancy can be obtained (i.e., whether the matches would be independent of illuminant). Our studies feature (1) control of adaptational state; (2) control of the observer's task (to match surface appearances, or to match chromaticities); (3) control of stimulus complexity (annular versus Mondrian-type displays); (4) use of standard and comparison stimuli with the same surrounds, to avoid unequal induction; (5) use of binocular vision, to avoid the standard haploscopic method in which standard and comparison are presented to different eyes and so fall on differently-adapted retinae.

The original study (Arend and Reeves, 1986, *Journal of the Optical Society of America (A)*, 3) showed that when the state of adaptation is kept roughly constant by requiring the observer to scan back and forth between comparison and standard displays, the extent of color constancy depends primarily on instruction and only very secondarily on stimulus complexity, although in the achromatic case, constancy also depends on depth relations (Schirillo, Reeves, and Arend, 1990). Color constancy is strong with surface appearance ("paper") matches, but weak or absent in chromaticity ("hue and saturation") matches (Arend, Reeves, Schirillo, and Goldstein, 1991). A similar pattern of results is obtained when standard and comparison displays are alternated, rather than being presented simultaneously (Reeves and Arend, 1992). This is important because color constancy would not be expected across two simultaneous displays if the visual system extracted a mean illuminant over the entire visual field. Therefore, the near absence of color constancy in the chromaticity task is especially significant in this experiment.

We have also asked subjects to set a single target paper in a single Mondrian to a specified unique color (red, green, blue, yellow, or grey). Once more, we have found color constancy to be poor in the chromaticity task. This result is important, because one might have argued that temporal averaging of the illuminants (rather than spatial) across displays occurred in the previous studies. Either spatial or temporal averaging would prevent color constancy.

The unique hue study controlled for this because only one display, with one illuminant, is seen in each block of trials.

We have also found approximate color constancy (near 80%) for the chromaticity instruction, when adaptation to the mean illuminant is produced by interposing 5 sec homogeneous adapting fields between stimulus presentations (Reeves and Arend, 1992). This result would be expected from classical (Von Kries-type) adaptation.

2. Adaptational History: Eye Tracker

We had planned to study the effect of the adaptational history on color appearence when the eyes are free to scan the display naturally. As previously reported, work with our Generation V SRI Purkinje Eye-tracker was halted by technical problems with the Eye tracker. We have now obtained a service contract for the Eye Tracker from Forward Technologies (Warren Ward), from May 1993 to May 1994, 1/3 rd. of which was paid by the URI grant. The machine is now in working order, but this only happened during the extension period to the grant, and there are no results to report yet.

3. Thresholds: Transient Tritanopia/Euchromatopsia

Work has been done with Michael Rudd and Stephen Grossberg to model transient euchromatopsia (i.e., transient tritanopia and its analogues in the red/green system). The essential finding is that turning off or down a colored background can greatly reduced the sensitivity of the red/green and yellow/blue hue pathways, even though normal dark adaptation (recovery of sensitivity) occurs for luminance. The standard model for this, of Pugh and Mollon, postulates a slow (15 sec time-constant) "restoring force" which builds up during light adaptation and suddenly rebounds when the light is turned off. This model, however, cannot handle the result (of Reeves) that transient euchromatopsia can be eliminated by 1 Hz flicker during the adaptation period. The new model employs two of Grossberg's theoretical circuits, an initial saturating stage followed by a gated dipole.

Work was done with James Schirillo to study the field additivity of the M-pathway, as isolated in varying spatial conditions including Stiles's. We found additivity in both Stiles' large spot and Stockman's tiny spot conditions, but strong evidence for cancellation (subadditivity) when field and test were co-incident (Foster's conditions). In the latter case, color appearence also changes. We suggest a role for opponent processes that depends on spatial configuration (Schirillo and Reeves, 1993).

4. Electrophysiology: Color

The PI has added some studies of the electro-retinogram to the work originally proposed, using Erich Sutter's M-sequence stimulation technique (Sutter and Tran, *Vision Res.*, 1992) to obtain maps of L-cone, M-cone, L-M, and L+M channels across the retina (Reeves, Wu, and Sutter, 1991, 1992; Sutter, Wu, and Reeves, 1993), using cone isolation and channel isolation methods. In addition, interactions between channels are being tested using the two-input M-sequence method. Results show that a simple picture of independent color (L − M) and luminance (L + M) processing channels may be incorrect. The preliminary data on this are complicated; for example, it appears that luminance responses influence the first-order kernel of the color response with a lag of two to four frames (each frame being

15 msec), but the color response does not influence the first-order kernel of the luminance response.

5. Electrophysiology: Spatial Effects: ERG

We (Yang, Reeves, and Bearse, 1990) showed that linear systems analysis can account for spatial factors in most published pattern electro-retinogram (PERG) work. Evidence for linearity was from contrast linearity and tests of superposition (the latter only in a limited way). We found a single band-pass spatial filter (scaled for the periphery) can account for data from 13 PERG studies employing a wide variety of 2-D patterns (checks, gratings, annuli, full-fields). We also found evidence that the ERG was approximately linear with contrast, as must be the case for this approach to be viable, and linear with the extent of spatial displacement (Wu, Reeves, and Armington, 1992). However, the recent work with Sutter's method has shown non-linearities of the order of 20% of the total response in the fovea, and of up to 10% in the periphery. Thus the linear approximation may be reasonable only with full-field stimuli for which the foveal contribution is small, or with purely peripheral (annular) stimuli.

6. Electrophysiology: Spatial Effects: VEP

Additional work with cortical potentials (the VEP) has shown that the VEP is not linear with the extent of spatial displacement (Wu, Reeves, and Armington, 1992). It is well known that the VEP is not linear with contrast. Therefore, attempts to model VEP amplitude using simple linear spatial filters are not likely to succeed. However, we have found that the power of the VEP is approximately linear with contrast up to quite high contrasts (Yang and Reeves, 1991, 1993). We have also found that the power of the VEP (not amplitude) obeys superposition, using specially tailored stimulus waveforms (so-called weighted Hermite polynomials, or WHPs) which to some extent take into account the spatial inhomogeneity of the visual system. VEP power elicited by a sum of WHPs equals the sum of the powers elicited by each individual WHP; and the VEP power elicited by alternating between two WHPs equals the difference. At high contrasts, some saturation occurs, even for the VEP power. However, the measured responses to the WHPs can be used at all but the highest contrasts to permit synthesis of responses to other stimuli, as WHPs form an orthonormal basis set.

7. Publications: Papers during URI Grant Period

Arend, L.E., Reeves, A., Schirillo, J., and Goldstein, R. (1991). Simultaneous color constancy: Papers with diverse Munsell values. *Journal of the Optical Society of America (A)*, **8**, 661–672.

Lemley, C. and Reeves, A. (1992). How visual imagery interferes with visual perception. *Psychological Review*, **99**, 633–649.

Peli, E., Yang, J., Goldstein, R., and Reeves, A. (1991). Effect of luminance on suprathreshold contrast matching. *Journal of the Optical Society of America (A)*, **8**, 1352–1359.

Reeves, A. (1992). Areas of confusion and ignorance in color science. *Behavioral and Brain Sciences*, **15**, 49–50 (Commentary).

Reeves, A. (1993). The visual perception of time: Temporal resolution. In W. Prinz and B. Bridgeman (Eds.), **Handbook of perception and action: Volume 1: Perception.** New York: Academic Press.

Reeves, A. and Bearse, M. (1991). The luminance dependence of the pattern-evoked electro-retinogram. In B. Blum (Ed.), **Channels in the visual nervous system: Neurophysiology, psychophysics and models.** Tel Aviv: Freund Publishing.

Schirillo, J., Reeves A., and Arend, L.E. (1990). Perceived lightness, but not brightness, of achromatic surfaces depends on perceived depth information. *Perception and Psychophysics*, **48**, 82–90.

Wu, S., Armington, J.C., and Reeves, A. (1992). Electroretinograms (ERGs) and visual evoked potentials (VEPs) elicited by pattern displacement. *Visual Neuroscience*, **8**, 127–136.

Yang, J. and Reeves, A. (1991). The harmonic oscillator model of early visual image processing. *SPIE Visual Communications and Image Science*, **1606**, 520–530.

Yang, J., Reeves, A., and Bearse, M. (1991). Spatial linearity of the pattern electroretinogram. *Journal of the Optical Society of America (A)*, **8**, 1666–1673.

Papers under Submission or Review

Sutter, E., Wu, S., and Reeves, A. (1993). The ERG elicited by red/green modulation in relation to isoluminance. Submitted to *Journal of the Optical Society of America (A)*.

Schirillo, J. and Reeves, A. (1993). Field additivity of the middle-wave cone pathway. Submitted to *Vision Research*.

Yang, J. and Reeves, A. (1993). Bottom-up visual image processing probed with weighted Hermite polynomials. Submitted to *Neural Networks*.

Published Abstracts of Presentations at Meetings (typically one or two paragraph summaries; all IOVS and ECVP Abstracts are refereed; IOVS refers to the Investigative Ophthalmology and Visual Science, ARVO Supplement)

Craver-Lemley, C.E., Arterberry, M.E., and Reeves, A. (1993). The effects of orientation and depth on imagery-induced interference with vernier acuity. 16th ECVP, Edinburgh, Scotland, June.

Craver-Lemley, C.E. and Reeves, A. (1992). Imagery-induced interference for acuity is not due to attentional distraction. Fourth Annual American Psychological Society Convention, San Diego, California, June.

Reeves, A. and Arend, L.E. (1992). Color constancy. OSA: Advances in Color Vision, Irvine, California, January.

Reeves, A. and Kurlyo, D. (1993). Attention can enhance orientation processing. IOVS 34.

Reeves, A. and McLellan, J. (1993). Saccading left while shifting attenton right. 16th ECVP, Edinburgh, Scotland, June.

Reeves, A. and Tijus, C. (1990). The pop-out effect in a simple 3D visual matching task. Cognitiva, Madrid.

Reeves, A. and Tijus, C. (1990). Extremely rapid visual erasure. IOVS 31.

Reeves, A. and Wu, S. (1991). Color opponency in the PERG. Presented to the annual meeting of the International Society for Clinical Electrophysiology of Vision, Sarasota, Florida, April 1991.

Reeves, A., Wu, S., and Sutter, E. (1991). Isoluminance and hetero-chromatic ERG responses across the retina. IOVS 33.

Reeves, A. and Yang, J. (1990). Contrast linearity and superposition of visual potentials evoked by pattern-reversing weighted Hermite Polynomials. OSA, Boston, November 1990.

Schirillo, J. and Reeves, A. (1990). Spatial factors determining field additivity of the middle-wavelength cone pathway. OSA, Boston.

Schirillo, J. and Reeves, A. (1991). Spatial factors and mechanisms of the middle wavelength cone pathway. IOVS 32.

Ward, A.S., Corwin, J., Reeves, A., and Fukui, T. (1990). Picture fragment identification in aging and Alzheimer's disease. New York Academy of Sciences, March 1990.

Wu S., Armington, J.C., and Reeves, A. (1990). Linearity and non-linearity of visual responses evoked by pattern displacement. IOVS 31.

Wu, S., Armington, J.C., and Reeves, A. (1990). Isolation of middle-wave cones in the ERG. *Perception*, **19**, 4, A34c (ECVP Supplement).

Wu, S., Sutter, E., and Reeves, A. (1992). Isoluminance in the ERG. OSA: Non-Invasive Assessment of the Visual System, Sante Fe, New Mexico, January.

Yang, J., Peli, E., Goldstein, R., and Reeves, A. (1990). The effects of luminance on super-threshold contrast matching. IOVS 31.

Yang, J., Peli, E., Goldstein, R., and Reeves, A. (1990). The effect of luminance on supra-threshold contrast matching. IOVS 31.

Yang, J. and Reeves, A. (1990). A polynomial basis function for vision: Tests with visual evoked potentials. *Perception*, **19**, 4, A77a (ECVP Supplement).